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MINA RAIS-ZADEH

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THE REGENTS OF THE UNIVERSITY OF MICHIGAN
3003 SOUTH STATE STREET 1058 WOLVERINE TOWER
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14. ABSTRACT

This project was focused on the development of switches using phase change materials from chalcogenide compounds. New phase change device structures were developed and a new thermoelectric model capable of describing the device nonlinear behaviors was introduced and validated.

15. SUBJECT TERMS
phase change materials (PCM), microelectromechanical systems (MEMS)

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Prescribed by ANSI Std. Z39.18

20150515036

Micro-Devices Using Resistance Change Materials (MODERN Materials)

PI: Mina Rais-Zadeh

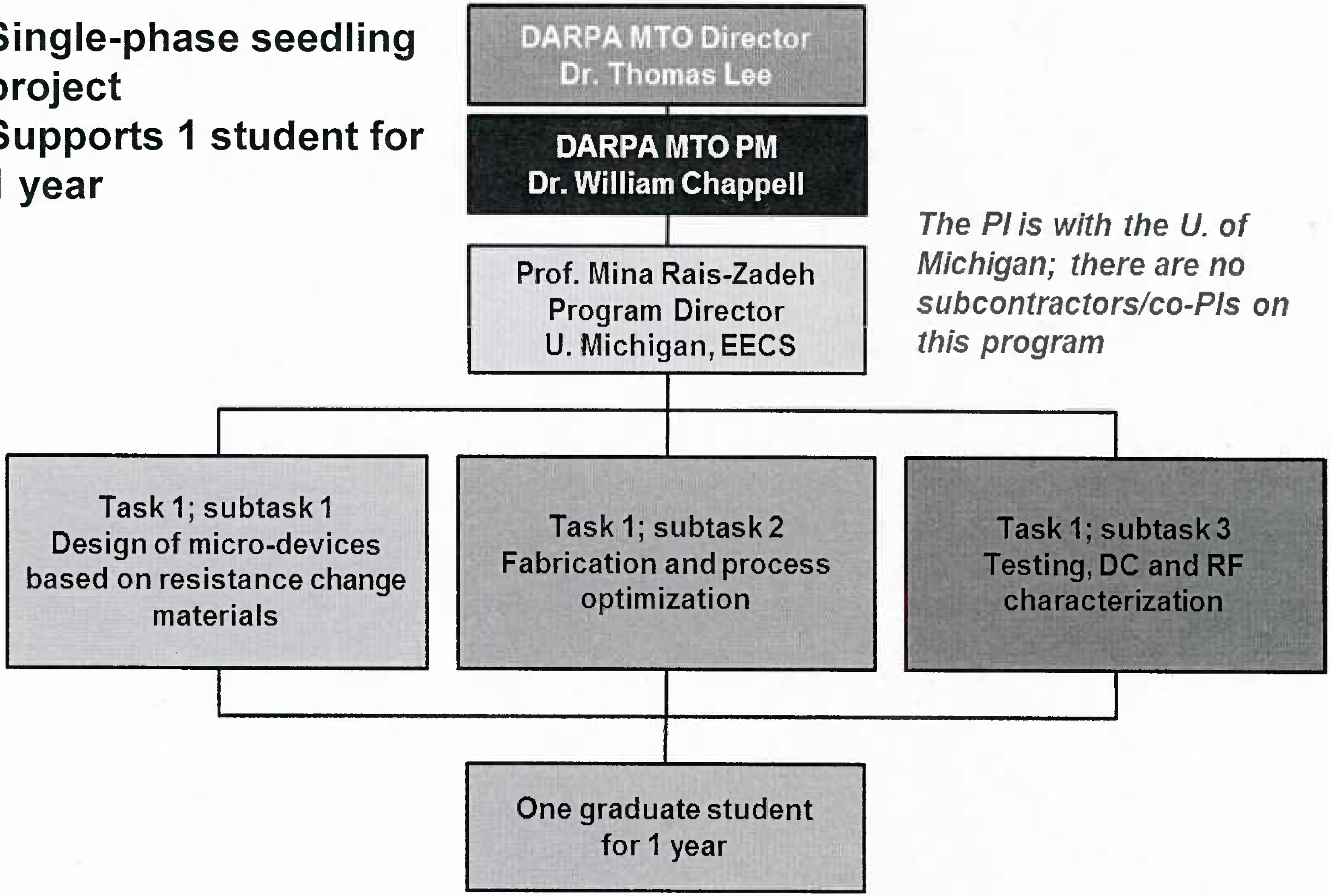
University of Michigan, Ann Arbor, MI

DARPA Final Review Meeting

03/07/2014

Organization Chart

- **Single-phase seedling project**
- **Supports 1 student for 1 year**



The PI is with the U. of Michigan; there are no subcontractors/co-PIs on this program

Outline

- Motivation & Introduction
- GeTe Vias as RF Ohmic Switches
  - Intrinsic RF Properties
  - Phase-Transition Characteristics
  - Power Handling Capability
- New GeTe Switch Design
  - Design Consideration
  - RF & Heat Simulation
  - Initial Measurement Result
- Future Plans

Outline

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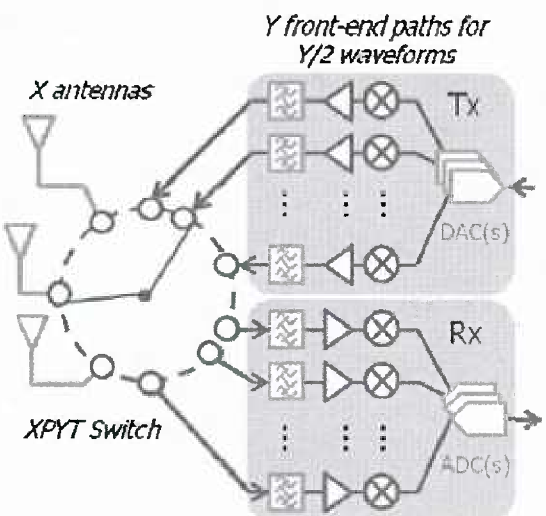
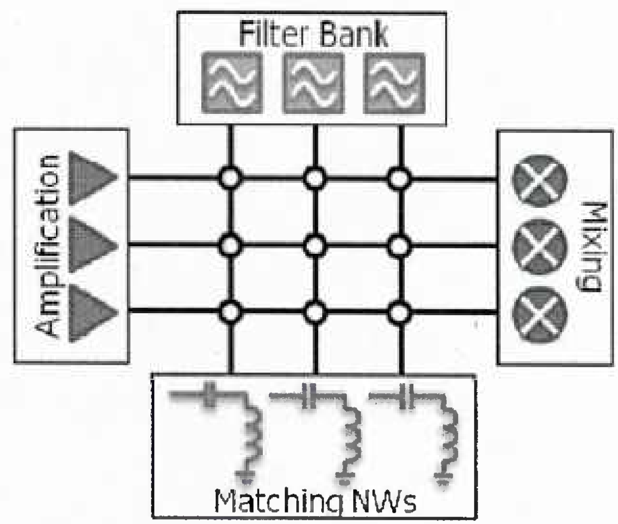
RF-FPGA Program Goal

- To enable a common hardware architecture that facilitates reutilization of the same set of RF front-end components across different applications making the transceiver chain programmable.
- "…this goal can only be achieved by investigating the ability to adapt, switch or otherwise alter the RF front end."
- This project is focused on the implementation of a new RF switch using resistance change or phase change materials.



Conventional concept of reconfigurable front-end



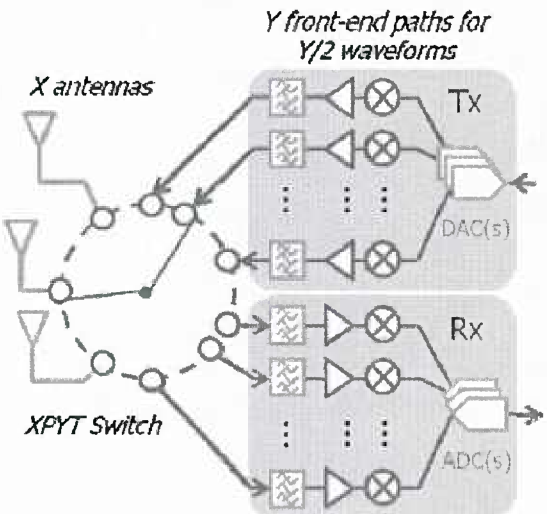
Finer grain of adaptability in analog and RF blocks

From DARPA-BAA-12-13, RF FPGA

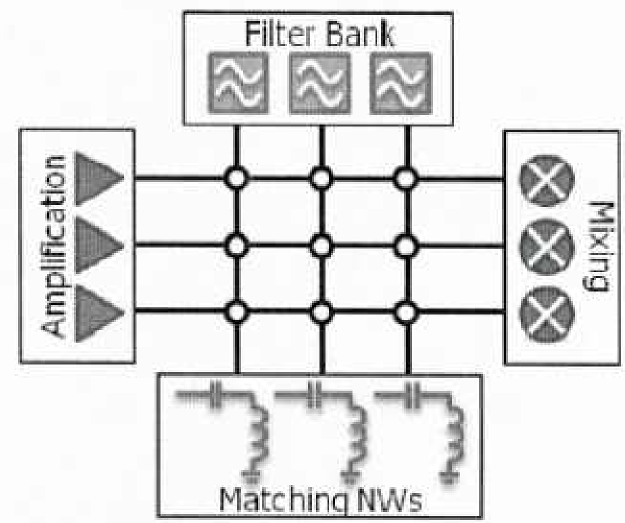
RF Switches - Requirements

- Low insertion loss & good isolation
- Small size (high-density integration)
- High yield and reliability
- Fast switching speed
- High power handling capability
- Post CMOS/Si compatibility? (note there are high power GaN RF switches with ns switching time and >10W power handling capability)

- These all can be potentially achieved using phase change switches



Conventional concept of reconfigurable front-end

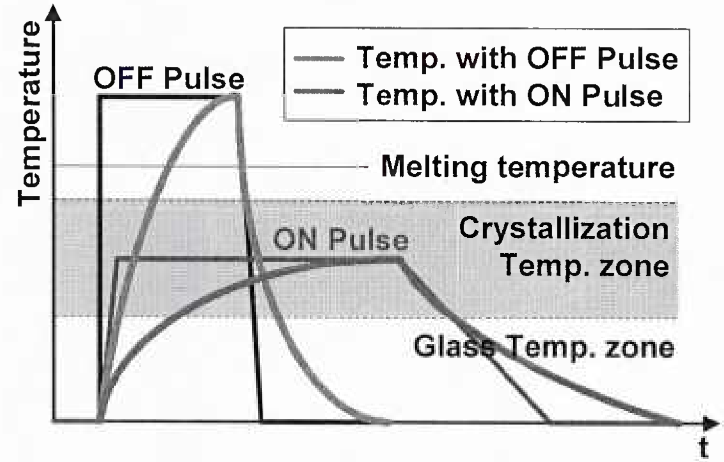


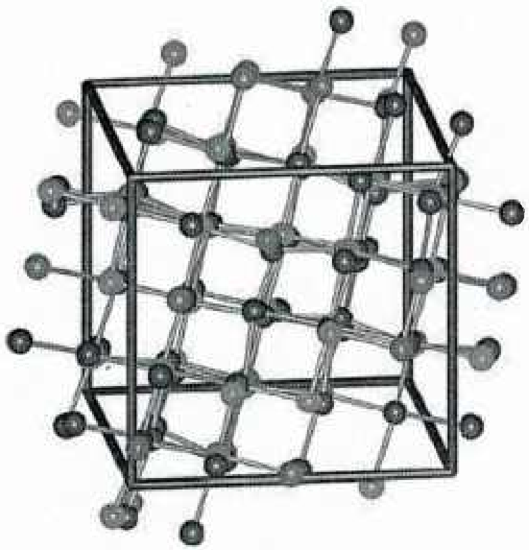
Finer grain of adaptability in analog and RF blocks

From DARPA-BAA-12-13, RF FPGA

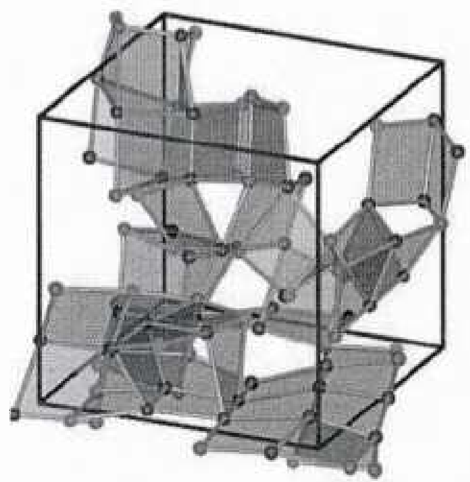
Phase Change Materials

- Two phases: amorphous and crystalline states
- Phase transition occurs when a specific heat condition is applied

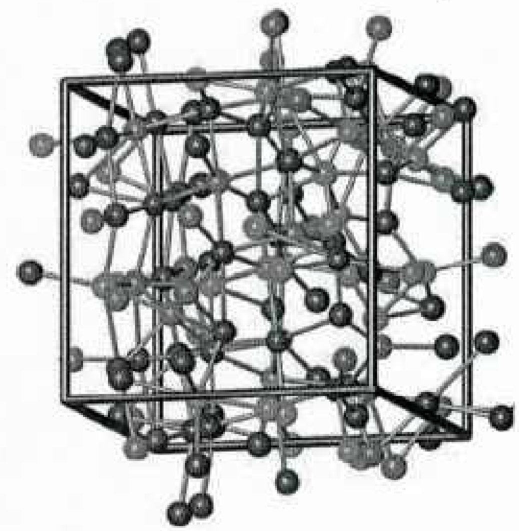




Crystalline state (low resistance)



$Ge_2Sb_2Te_5$ melt

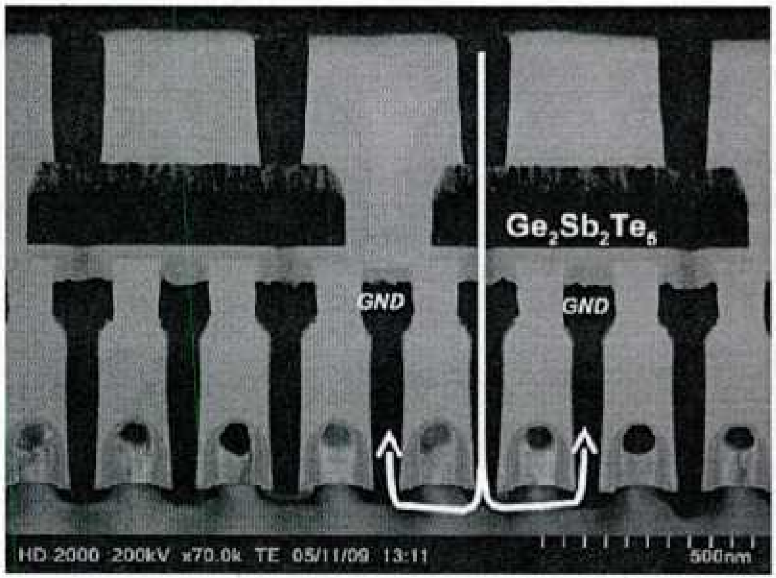


Amorphous state (high resistance)

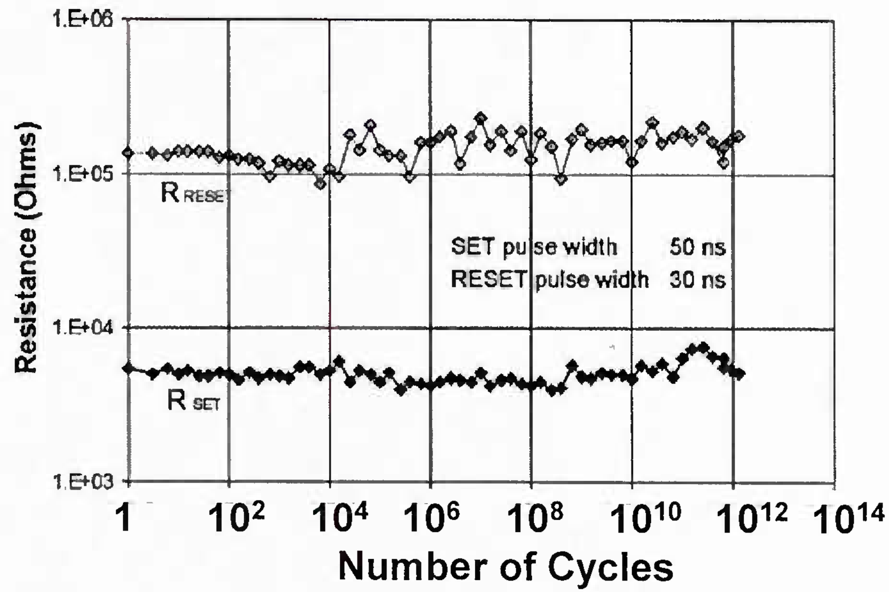
J. Hegedus and S. R. Elliott, Nature Materials, 2008.

Phase Change Materials

- **Benefits: high-density integration, fast switching speed (ns range), long life cycles (> 10^8 or 10^9)**
- **Exploited as non-volatile random-access memory or optical DVD**



256 Mb PRAM using 100nm technology; a cell size is 0.166 μm²

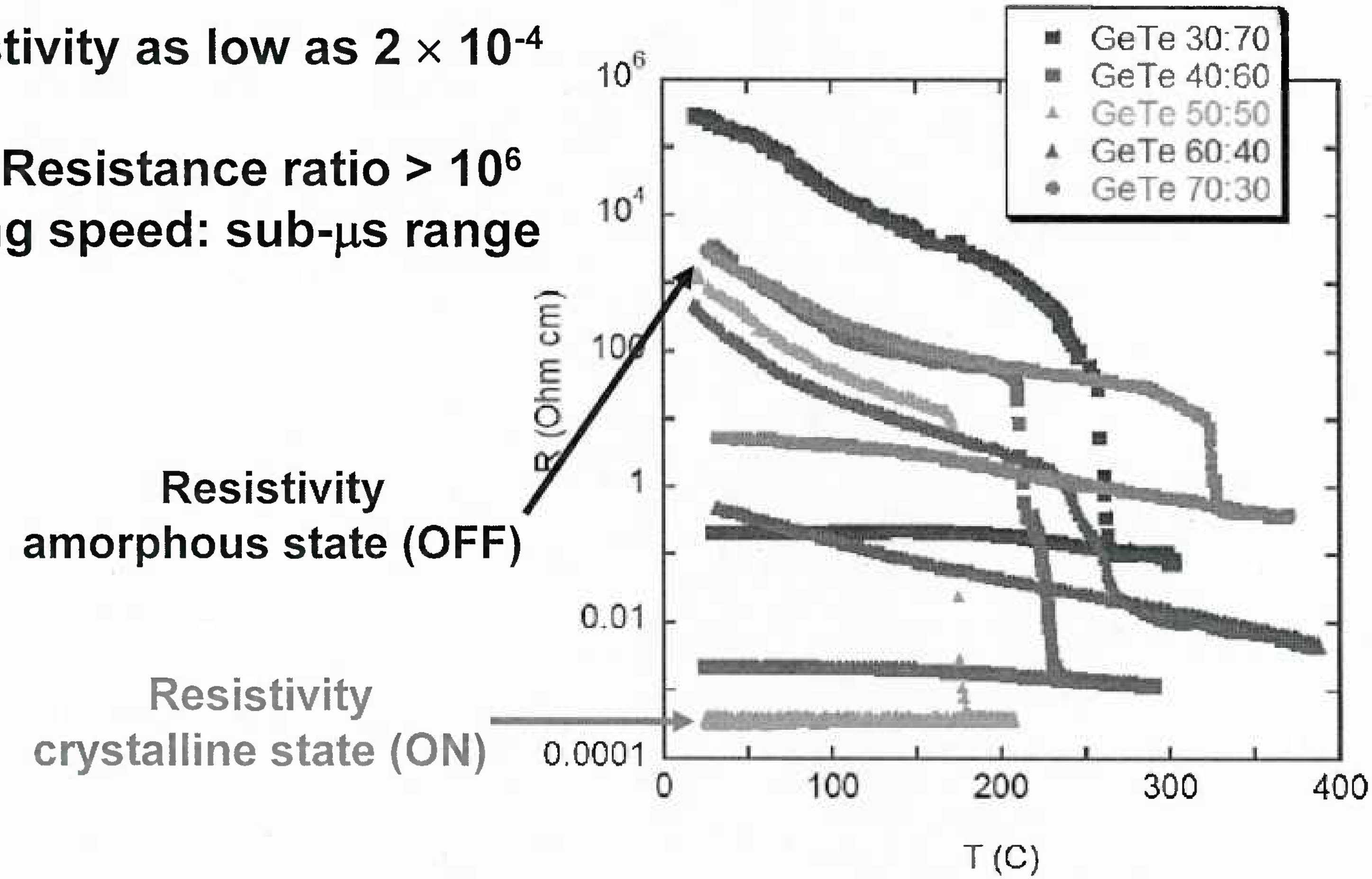


Cycling performance of the set and reset states of a single PC memory cell

S. Kang, et al, IEEE JSSC, 2007.
S. Lai and T. Lowrey, IEEE IEDM, 2001.

Material Choice for RF Switching: GeTe

- ON resistivity as low as 2×10^{-4} $\Omega\cdot$cm
- OFF/ON Resistance ratio > 10^6
- Switching speed: sub-μs range



Resistivity vs. temperature in various stoichiometric composition of GeTe

S. Raoux, et al, EPCOS 2009, Sep. 2009.

Material Choice for RF Switching: GeTe

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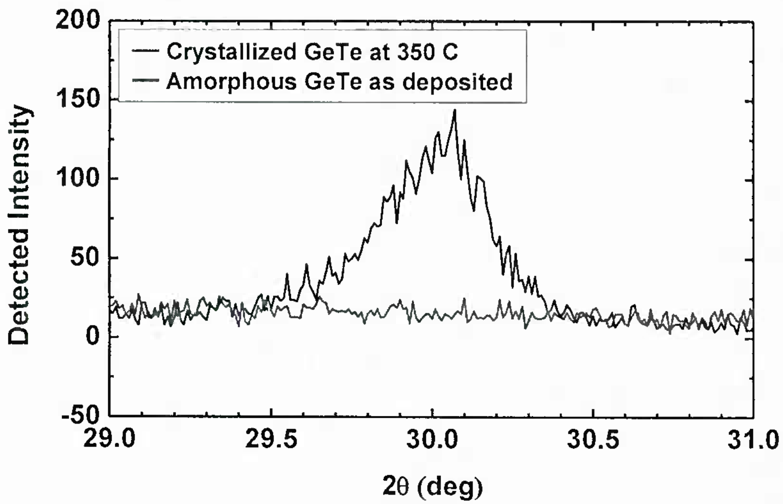
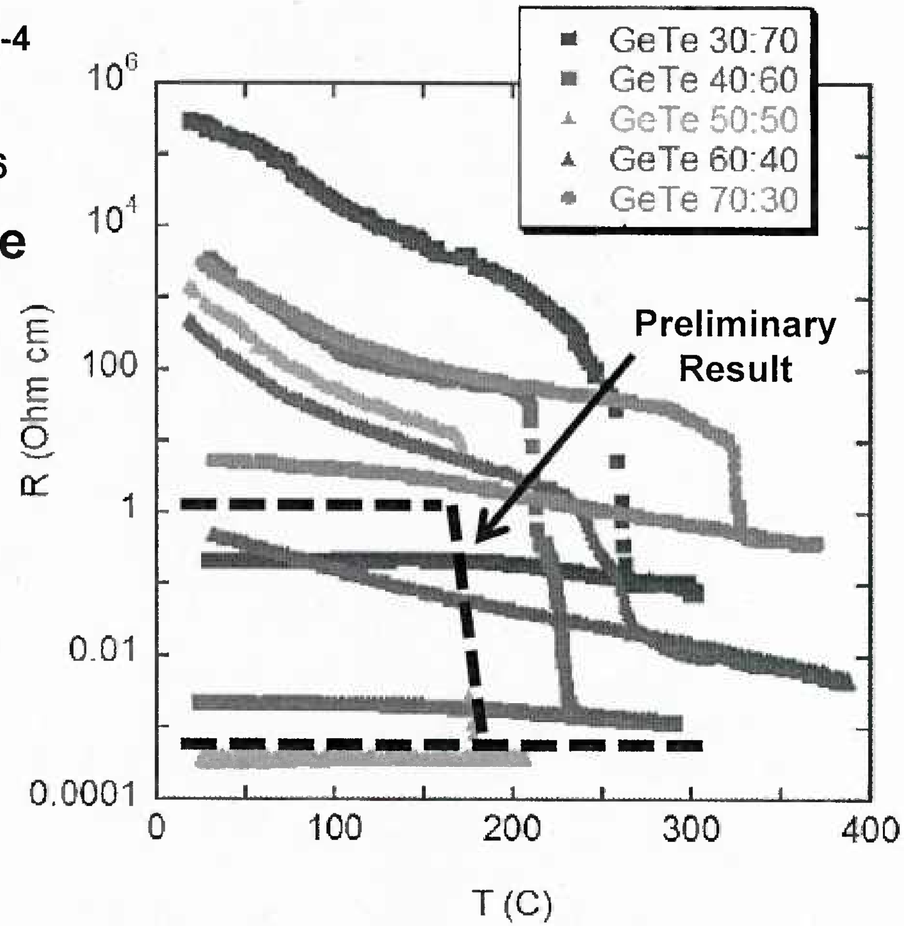


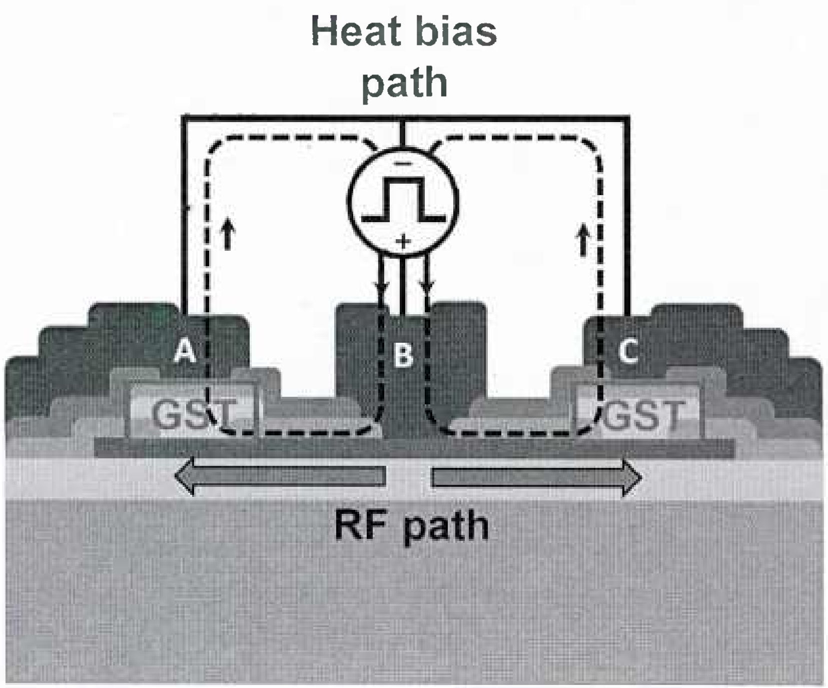
XRD plot of a GeTe thin film deposited on a silicon substrate from 29° to 31° of 2θ



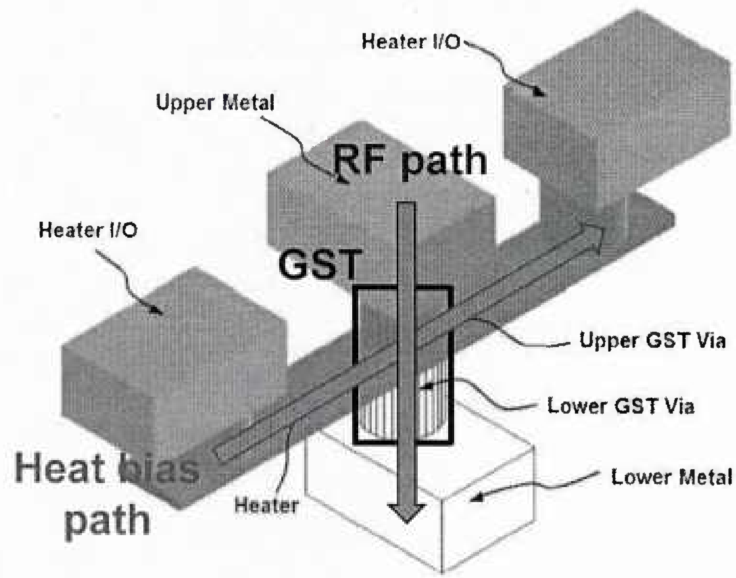
Resistivity vs. temperature in various stoichiometric composition of GeTe

Direct Heating vs. Indirect Heating

- Direct heating: same path for RF and heating bias
- Indirect heating: separated paths for RF and heating bias



Direct heating



Indirect heating

C.-Y. Wen, et al, IEDM 2010, Dec. 2010.
K. N. Chen, et al, IEEE EDL, Jan. 2008.

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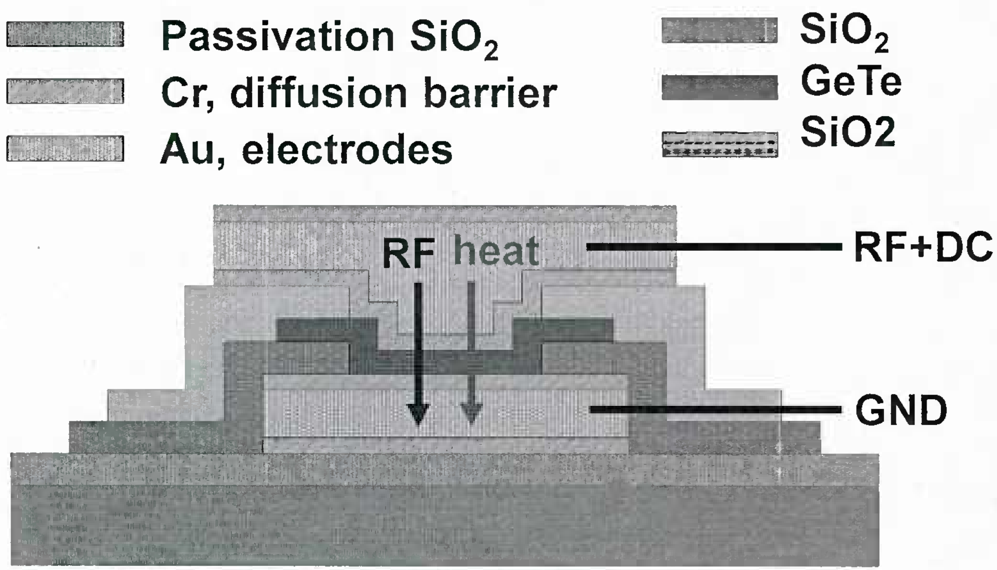
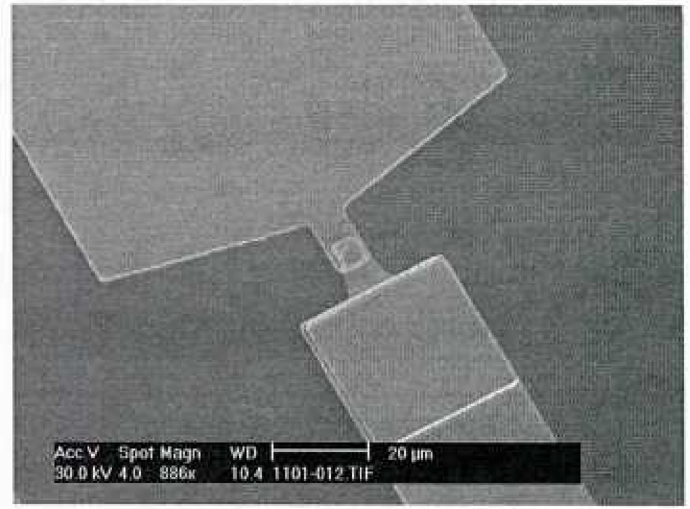
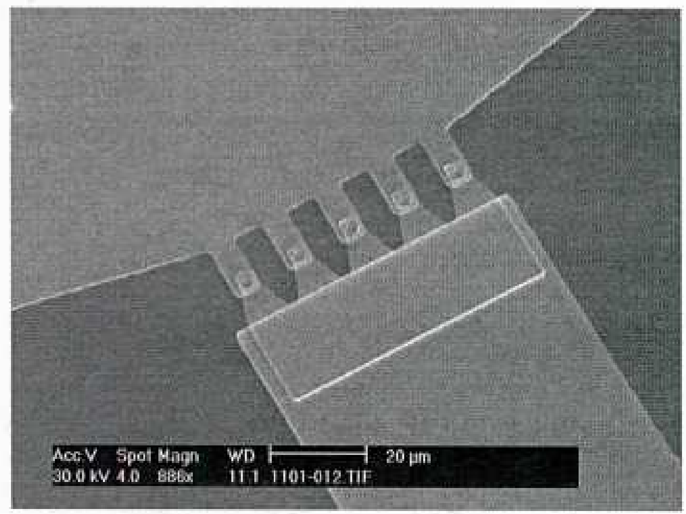
GeTe Vias as RF Ohmic Switches

- Fundamental properties of GeTe were characterized using two different switch configurations.
- Direct heating is used for phase transition.



Cross-section of PC switch

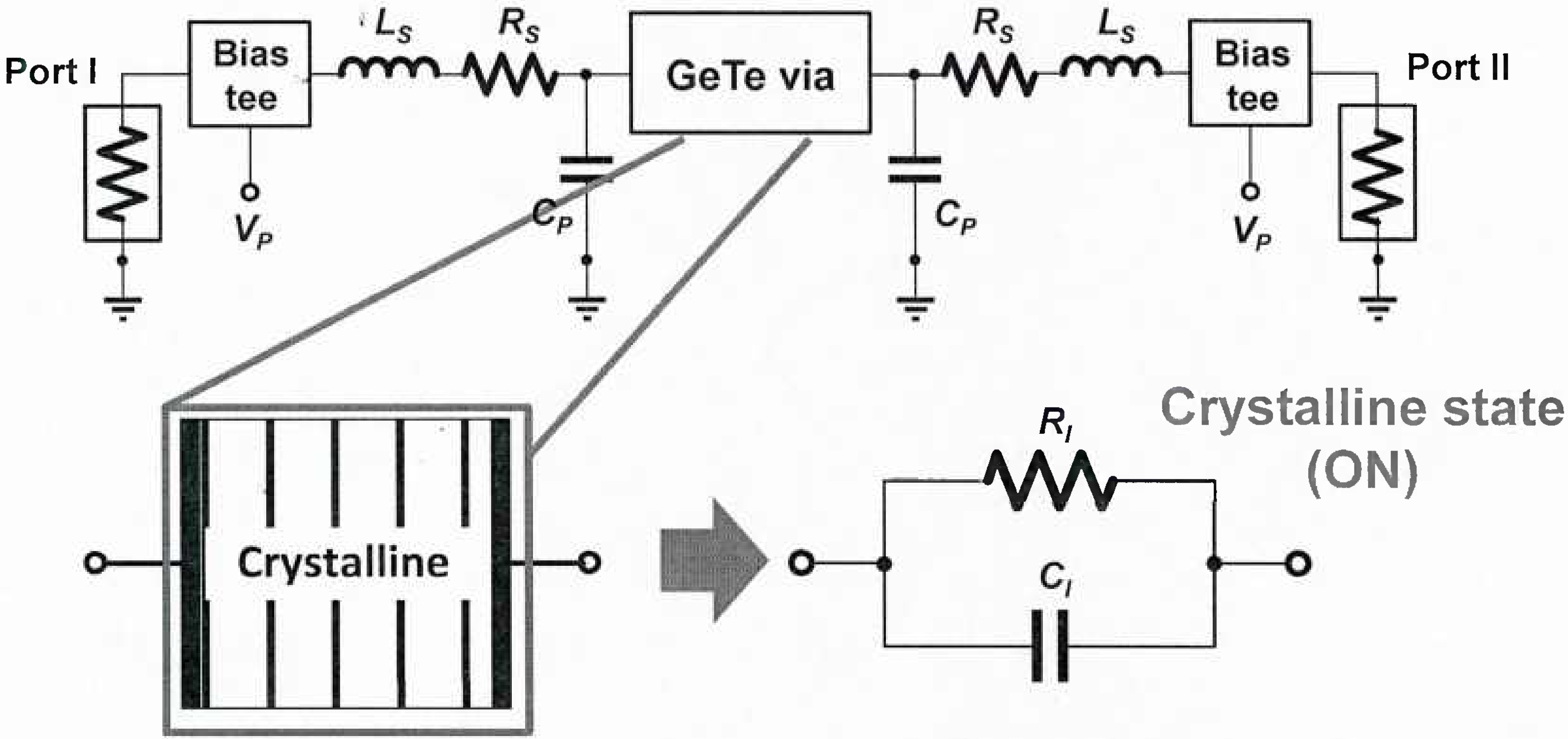




SEM view of fabricated PC switches

Intrinsic RF Properties
Equivalent Electrical Model

- A new electrical model is proposed for phase-change switches.
- GeTe via is conventionally modeled with a parallel connection of an intrinsic resistor and a capacitor.

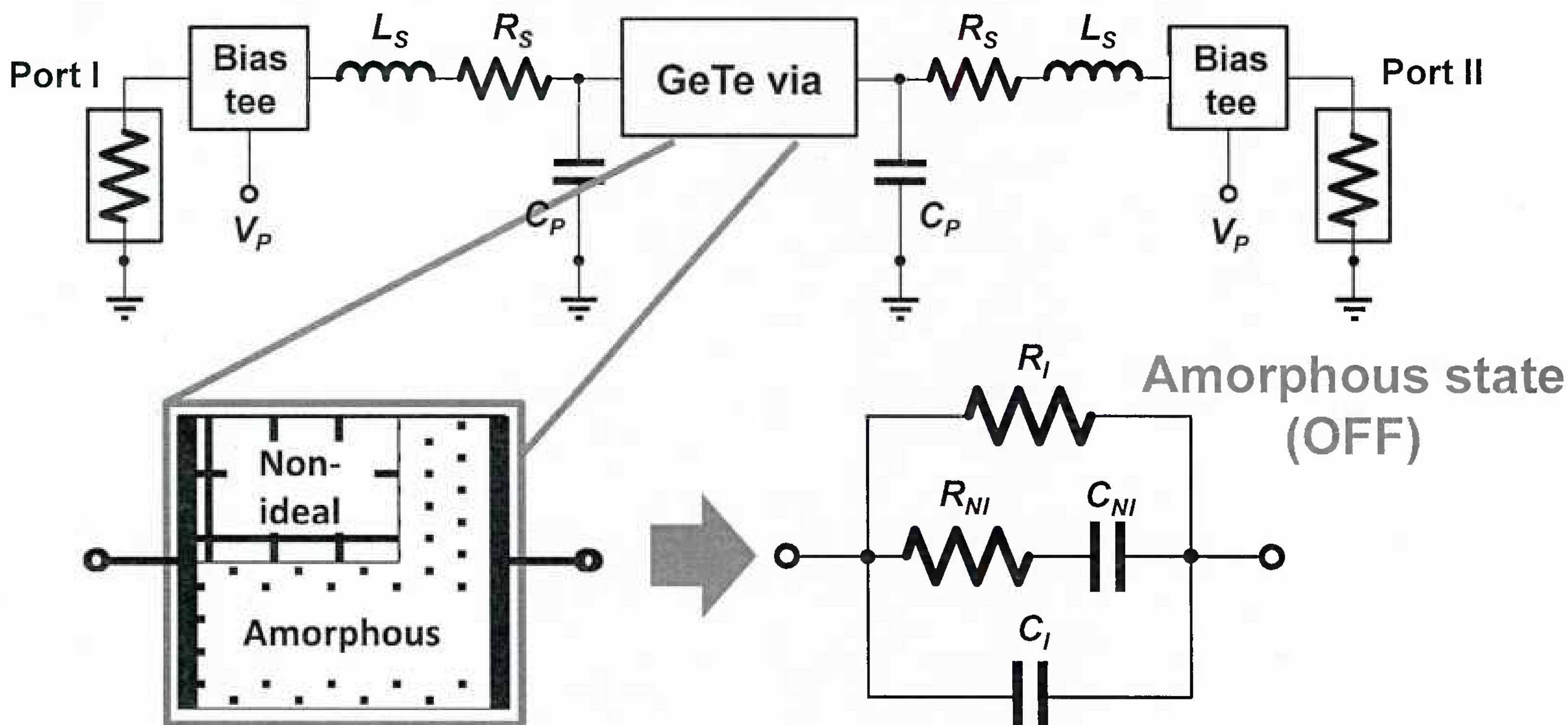


Illustrated diagram of GeTe via state

Equivalent electrical model

Intrinsic RF Properties
Equivalent Electrical Model

- With incomplete transition, non-ideal state grains could exist.
- Grains that undergo incomplete phase transition are modeled by adding another parallel branch to the electrical model
- Size reduction is important for good isolation at high frequency.

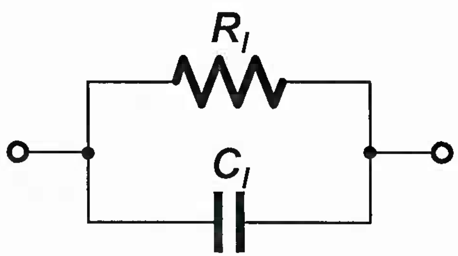


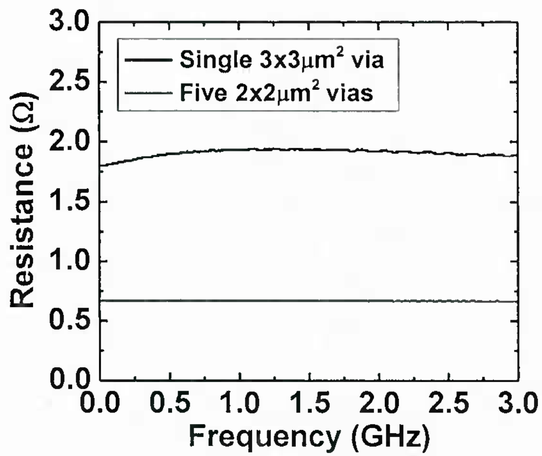
Illustrated diagram of GeTe via state

Equivalent electrical model

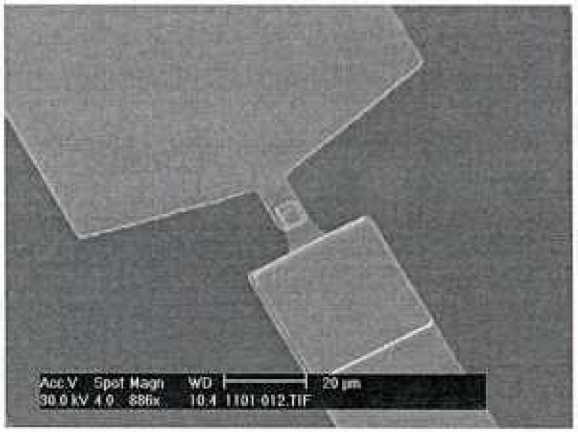
Intrinsic RF Properties
Lumped Element Values (Crystalline State)

- In the crystalline state (ON), R_I models the low resistance of the via.
- C_I is the intrinsic parallel plate capacitance (which cannot be ignored as the permittivity of the phase change layer is high.)

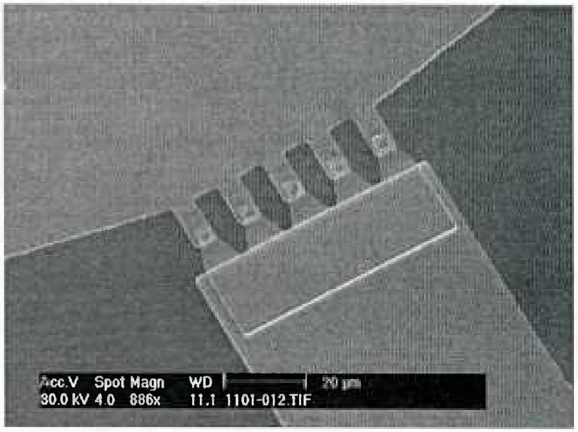




Extracted R_I
Crystalline state (ON)



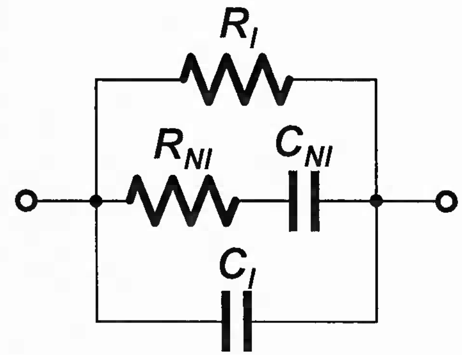
SEM view of single
3 × 3 μm² via

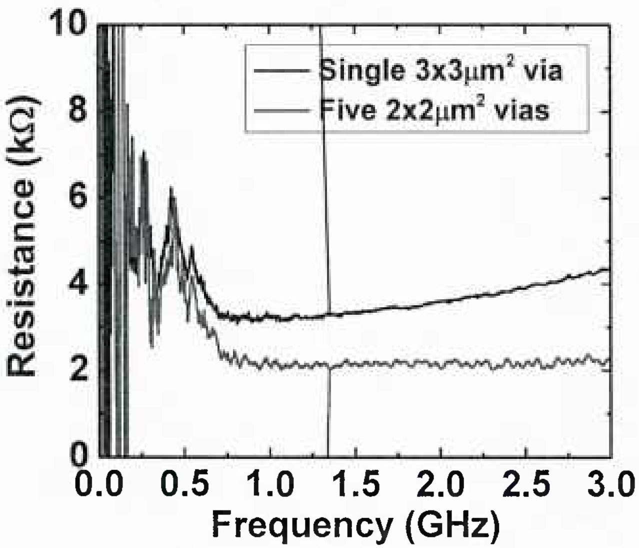


SEM view of five
2 × 2 μm² via

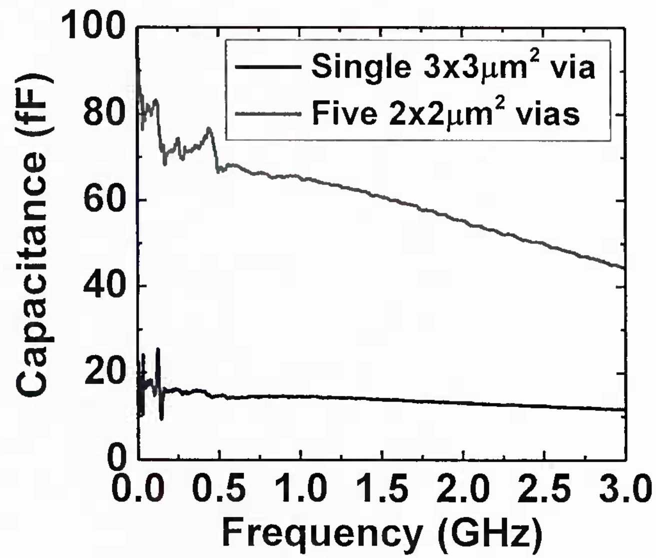
Intrinsic RF Properties
Lumped Element Values (Amorphous State)

- In amorphous state (OFF), R_I models the OFF state leakage resistance, reaching 10^5 times the ON resistance.
- At high frequencies, R_{NI} and C_{NI} provide additional feed-through path and reduce the isolation level (unwanted).





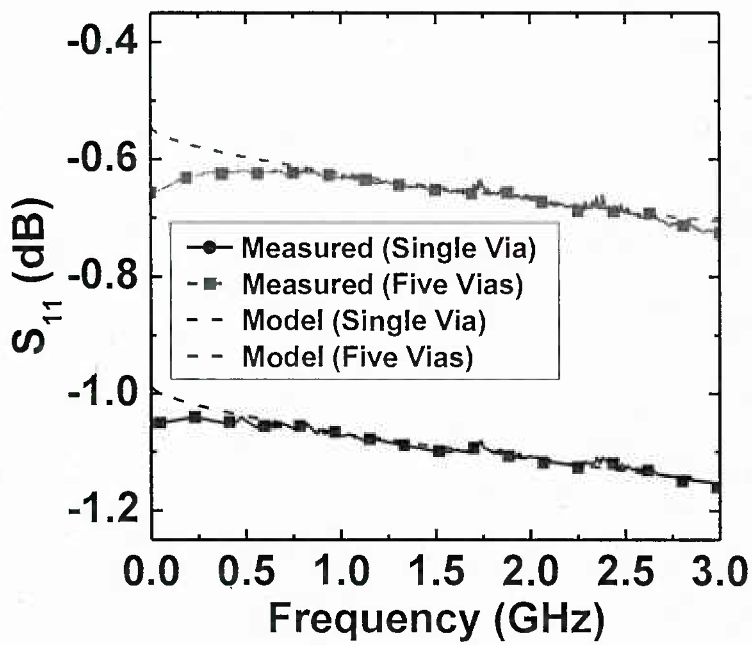
Extracted R_{NI}



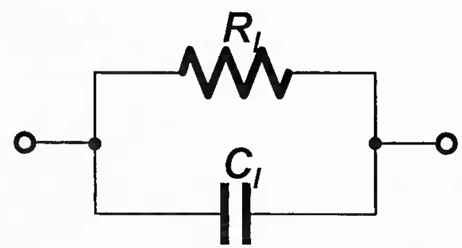
Extracted C_I

Intrinsic RF Properties
Measured S_{11} (Crystalline State)

- Measured S_{11} from one-port GeTe switches in single-via and five-via configurations.
- Parasitic capacitance of 5via device < 5x capacitance of 1via device



Measured S_{11} at crystalline state

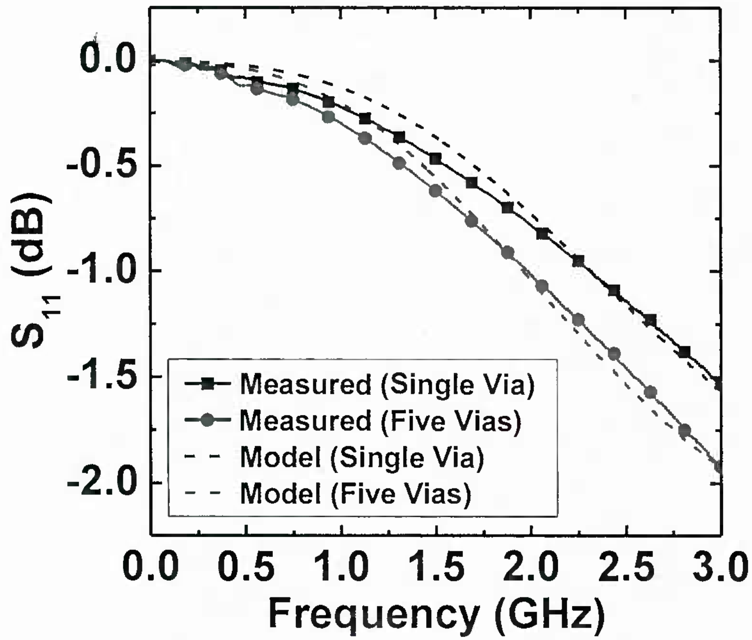


	Single via	Five vias
R_l	2.62 Ω	1.35 Ω
C_l	15 fF	60 fF
Cutoff Freq	4.0 THz	1.96 THz

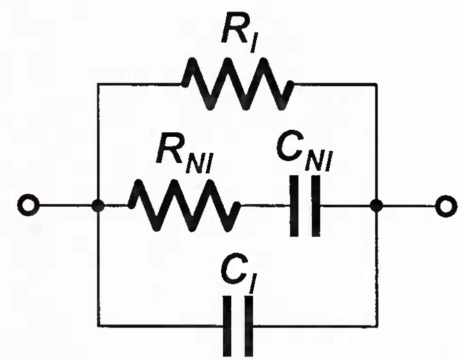
Lumped element values

Intrinsic RF Properties
Measured S_{11} (Amorphous State)

- Measured S_{11} from one-port GeTe switches in single-via and five-via configurations.
- As expected, the incomplete phase transition affect the OFF-state isolation at higher frequencies.



Measured S_{11} at amorphous state

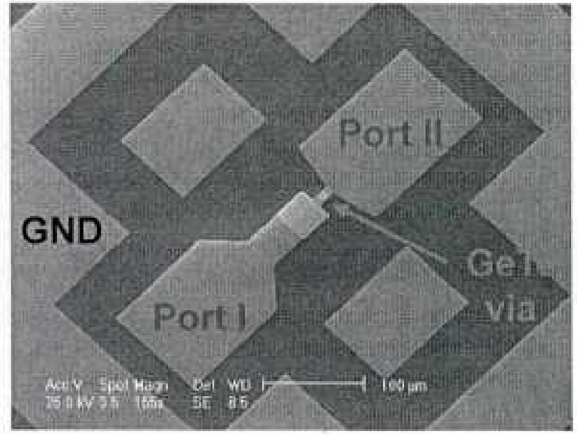


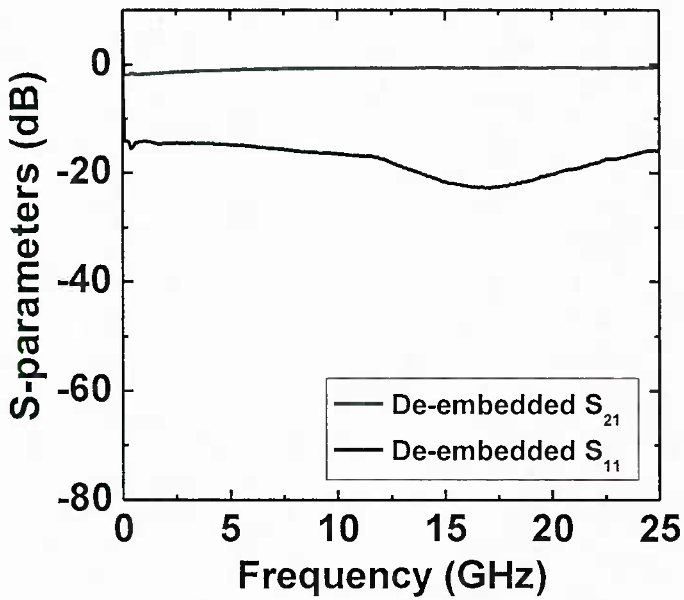
	Single via	Five vias
R_I	200 kΩ	100 kΩ
C_I	15 fF	60 fF
R_{NI}	6 kΩ	1 kΩ
C_{NI}	1 fF	1 fF

Lumped element values

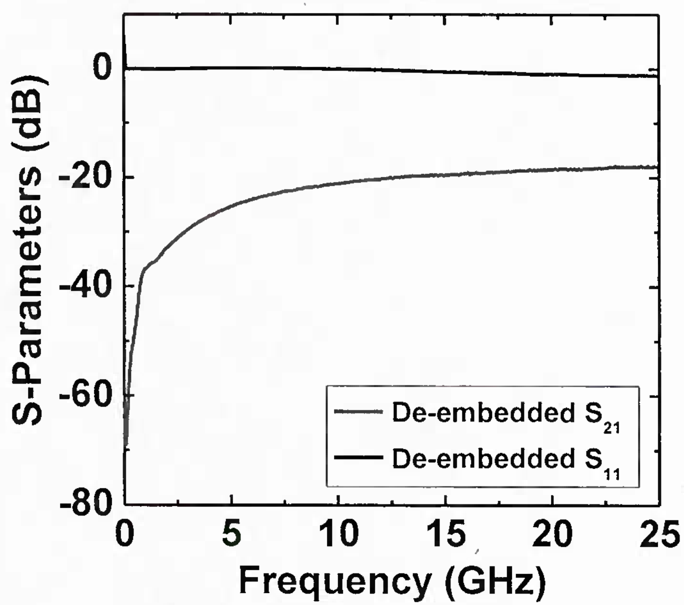
Intrinsic RF Properties
Measured S-Parameters (Two-Port)

- **Insertion loss (S_{21} at ON state)**
  - **0.5 dB @ 10 GHz, 1.0 dB @ 20 GHz**
- **Isolation (S_{21} at OFF state)**
  - **20 dB @ 10 GHz, 18 dB @ 20 GHz**





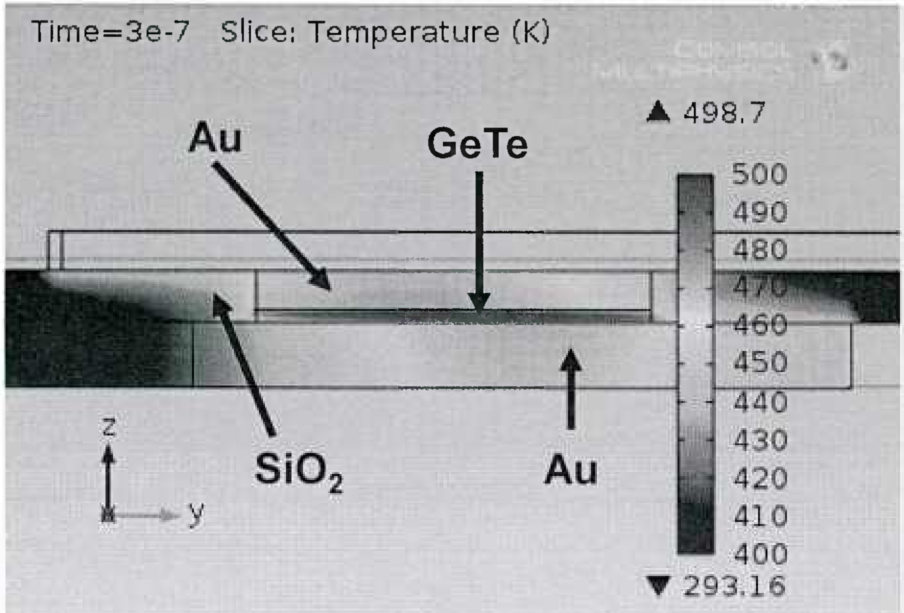
Crystalline state (ON)



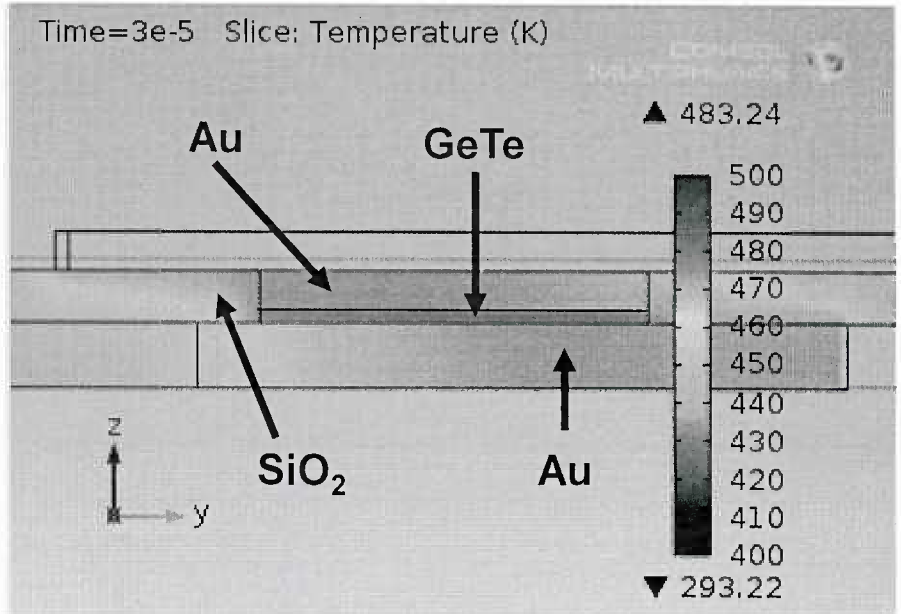
Amorphous state (OFF)

Intrinsic RF Properties
Phase-Transition Simulation

- **Amorphization time < 1 μs**
- **Crystallization time < 50 μs**



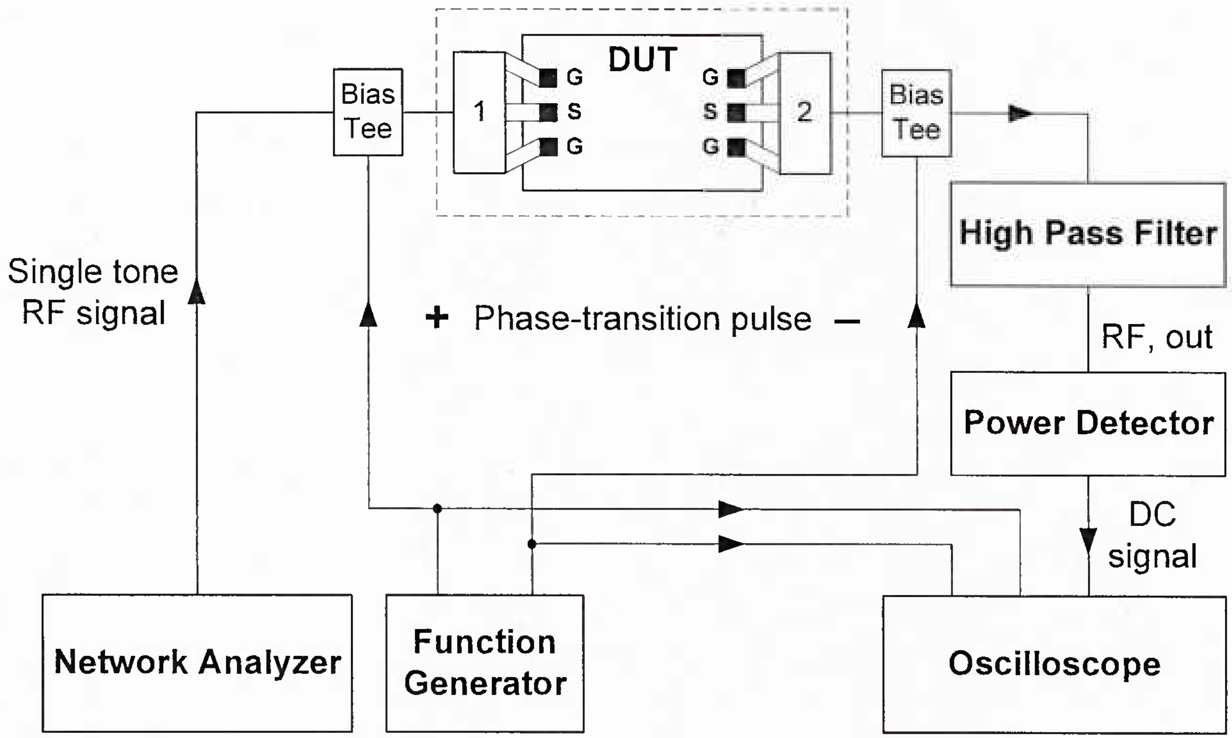
Simulated temperature distribution when 3.5 V is applied for 300 ns for amorphization



Simulated temperature distribution when 2.0 V is applied for 30 μs for crystallization

Intrinsic RF Properties
Measured Switching Speed

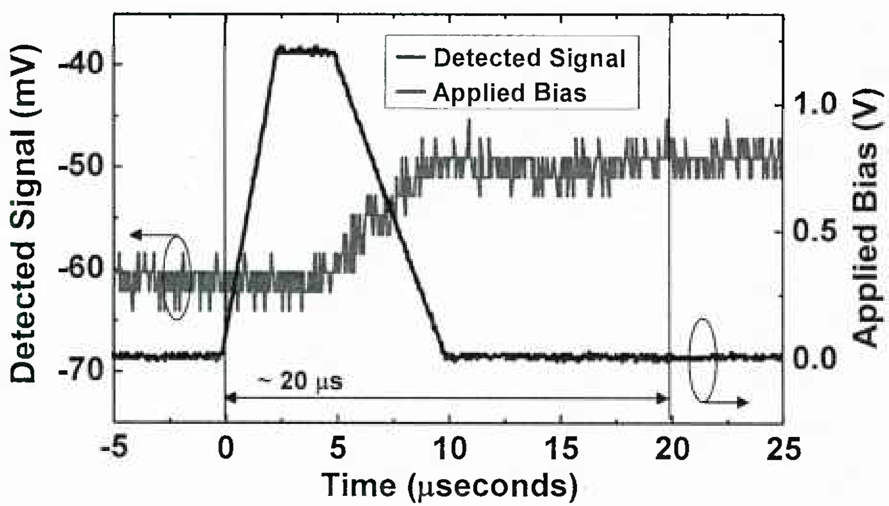
- **Phase transitions can be realized by applying voltage or current pulses to heat the GeTe material.**



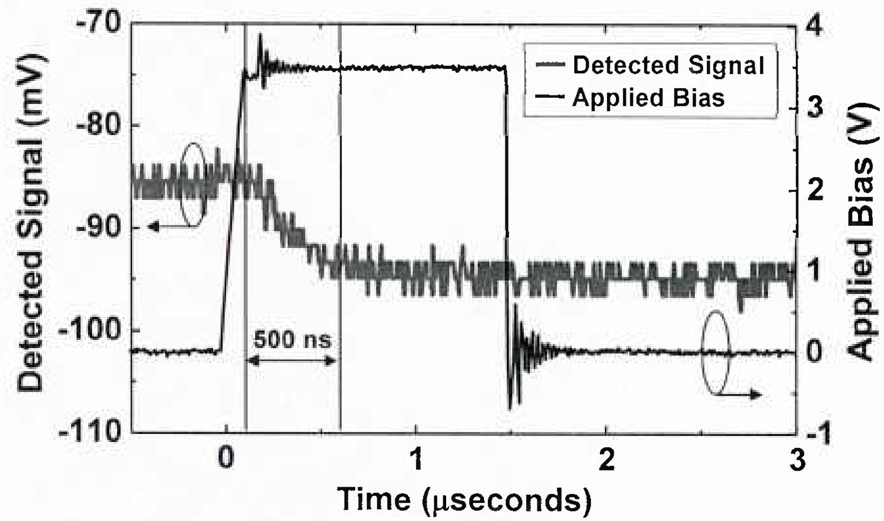
Measurement system diagram

Intrinsic RF Properties
Measured Switching Speed

- Crystallization takes ~ 20 μs.
- Amorphization takes < 1 μs.
- For more reliable switching, bias voltage amplitude and duration should be further adjusted and optimized.
- Also, smaller size vias will be placed in parallel to ensure complete phase transition, while maintaining a small ON resistance.



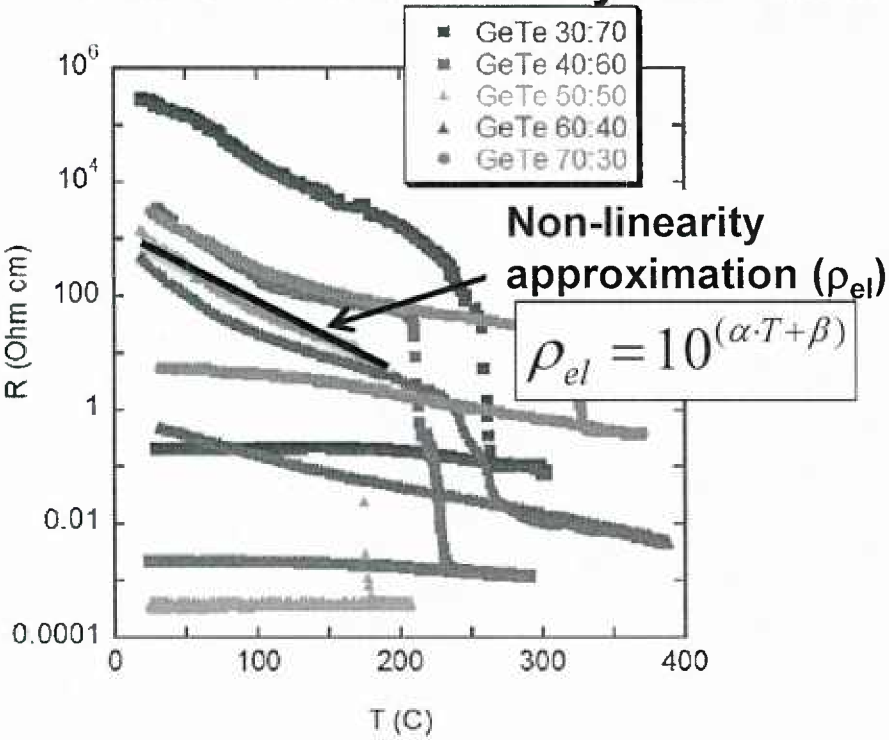
Switching characteristics for crystallization



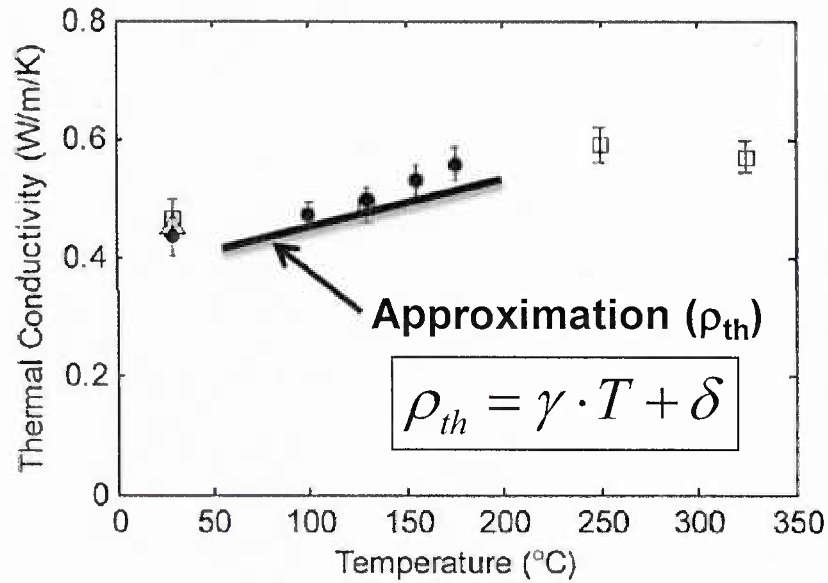
Switching characteristics for amorphization

Intrinsic RF Properties
Analysis on Power Handling Capability

- **Non-linear behavior of GeTe switches is dominantly observed at the amorphous state.**
- **Both electrical and thermal resistivites show temperature variation.**
- **This is accelerated by the Poole-Frenkel Effect.**



Electrical resistivity change



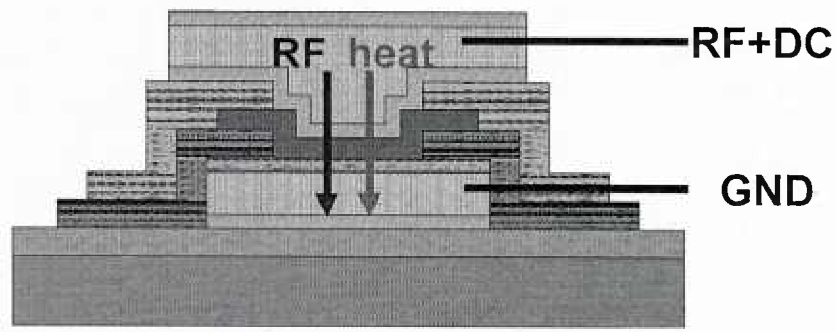
Thermal resistivity change

S. Raoux, et al, EPCOS 2009, Sep. 2009.
J. P. ReiFenberg et al., IEEE EDL, Jan. 2010.

Analysis on Power Handling Capability Overview

- A new power handling analysis model for GeTe switch is proposed and verified by comparing simulation and measurement results. This model can be utilized to estimate IIP_3 or P_{1dB} of various types of phase change switch structures and materials.

- The power handling performance of directly heated two-port GeTe is measured and compared with simulation results, showing good agreement.

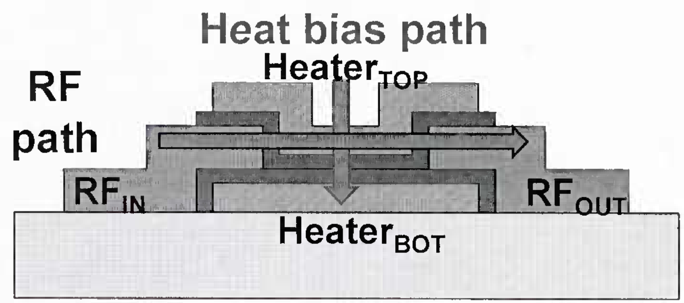


Type A: directly heated two-port GeTe switch

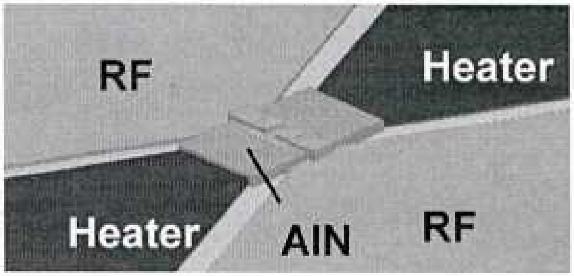
Analysis on Power Handling Capability Overview

- To improve the performance, Type B: a four-terminal switch with separate RF and heater electrodes is proposed and fabricated. Preliminary results show very promising performance.

- Other designs (Type C) are also under consideration that offer simpler fabrication process and better power handling capability (at the cost of higher power consumption).



Type B: four-terminal directly heated switch with separate RF and heater electrodes



Type C: four-terminal indirectly heated switch with separate RF and heater electrodes

Power Handling Analysis
Poole-Frenkel Effect

- The change in electrical resistivity in the amorphous state is dominated by the Poole-Frenkel Effect (electrical conduction in dielectrics due to thermal fluctuation under an electric field).
- Although this effect is not as dominant at the ON state due to a smaller voltage drop across the PC layer, resistivity change of GeTe can also be described when crystallized using the same model with different trapping energy level (E_c) and effective level of related carriers (N_T).

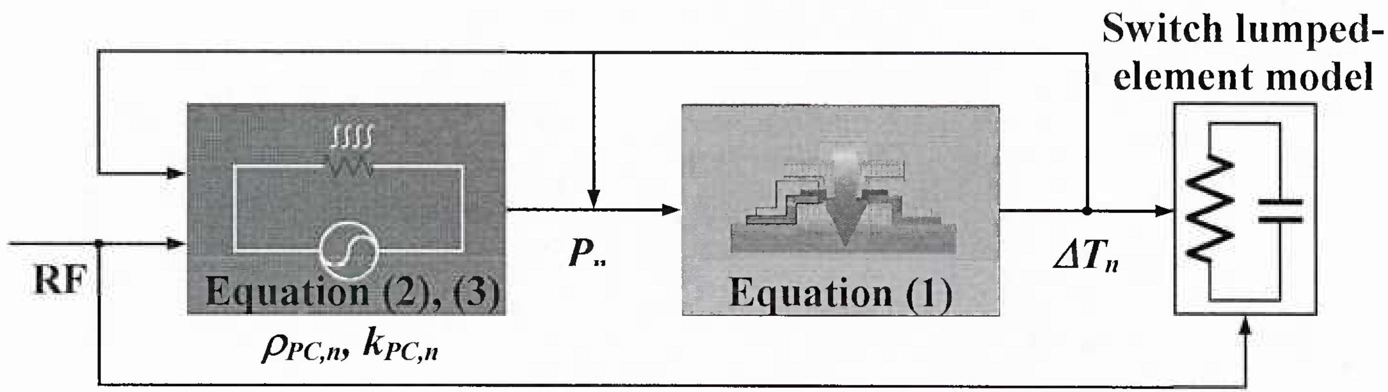
$$\rho_{PC} = \frac{kT \cdot \tau_0}{(q\Delta z)^2 \cdot N_T} \cdot e^{(E_C - E_F)/kT} \cdot \cosh^{-1}\left(\frac{qV}{kT} \cdot \frac{\Delta z}{2u_a} \right) + \rho_0$$

k, q, τ_0, E_F, *V,* Δz *and* u_a indicate Boltzmann constant, elementary charge, time constant for trapped electron, Fermi level, applied voltage, short trap distance, and effective thickness of PC layer, respectively

D. Ielmini and Y. Zhang, Journal of Applied Physics, 102, 054517 (2007).
John Simmons, Physical Review, 1967.

Power Handling Analysis Nonlinear Joule-Heating Model

- **Power handling capability (IIP_3, P_{1dB}) is analyzed using non-linear electro-thermal model of GeTe switches.**



Electro-thermal model of GeTe switch

$$H(\omega)=\frac{\Delta T}{P}=\frac{1}{V_E}\cdot\frac{t_E[(t_{PC}/k_{PC})\cdot((\tanh\beta_{PC})/\beta_{PC})+R_B]}{1+j\omega C_E t_E[(t_{PC}/k_{PC})\cdot((\tanh\beta_{PC})/\beta_{PC})+R_B]}$$

1: Heat transfer function

$$\rho_{PC}=\frac{kT\cdot\tau_0}{(q\Delta z)^2\cdot N_T}\cdot e^{(E_C-E_F)/kT}\cdot\cosh^{-1}\left(\frac{qV}{kT}\cdot\frac{\Delta z}{2u_a}\right)+\rho_0$$

2: Electrical resistivity modeling

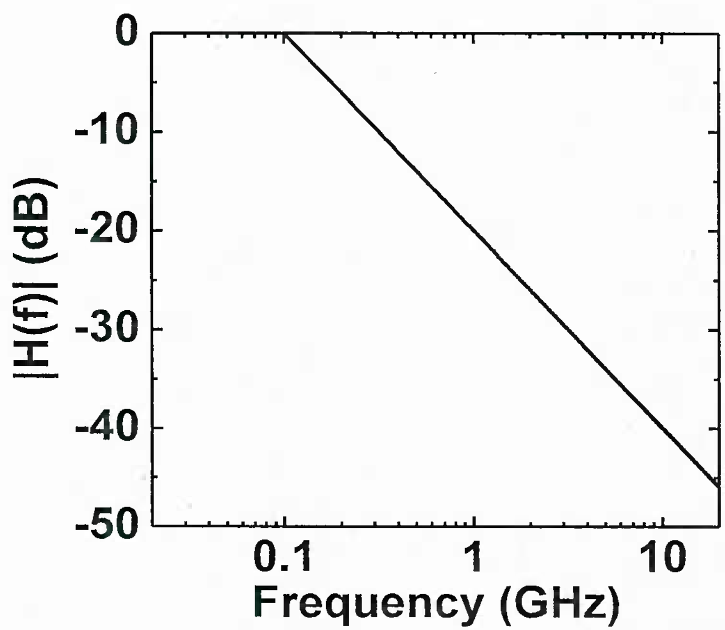
$$k_{PC}=a\cdot\exp[-(T-T_0)/b]+c$$

3: Thermal resistivity modeling

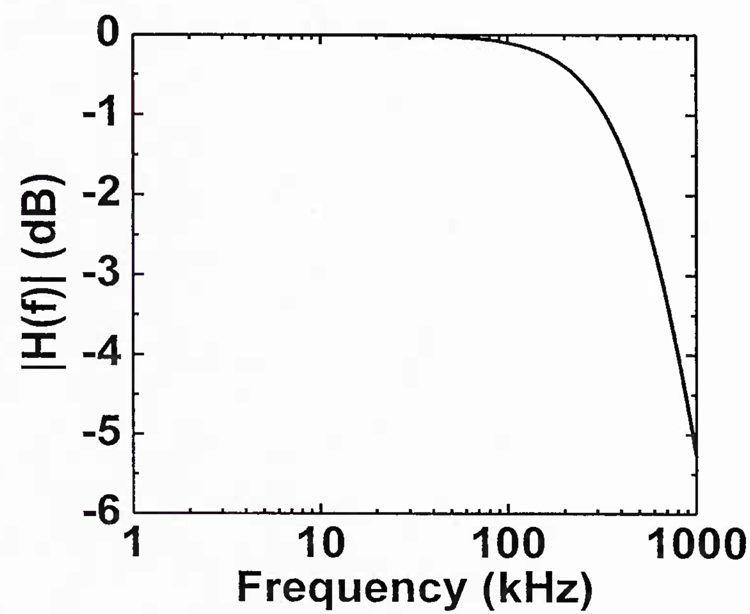
Y. Shim and M. Rais-Zadeh, IEEE EDL, 2014

Power Handling Analysis
Heat Transfer Function

- **Frequency response of heat transfer function shows low pass filtering behavior.**
- **For the simulated structure the thermal 3dB BW is ~600 kHz.**



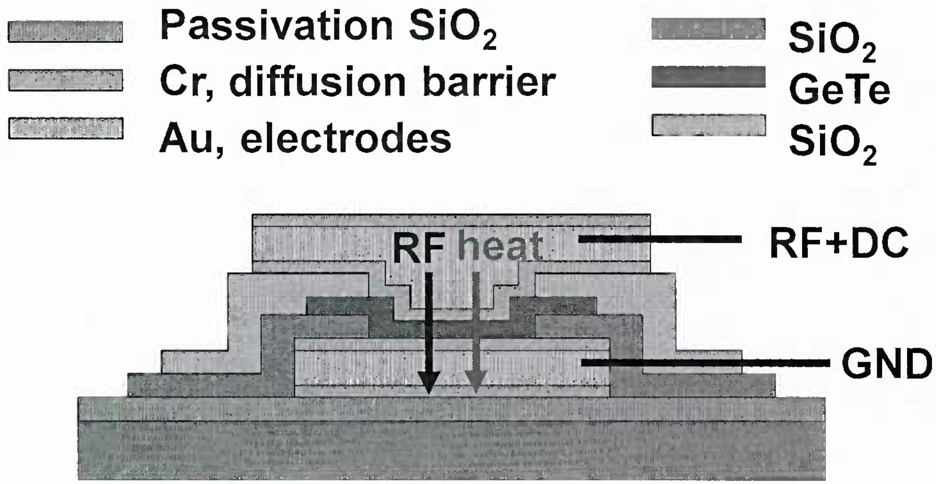
Heat transfer function
Frequency response up to 20 GHz

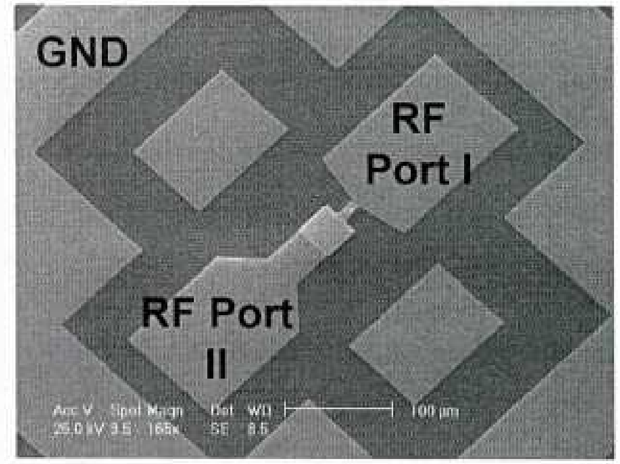


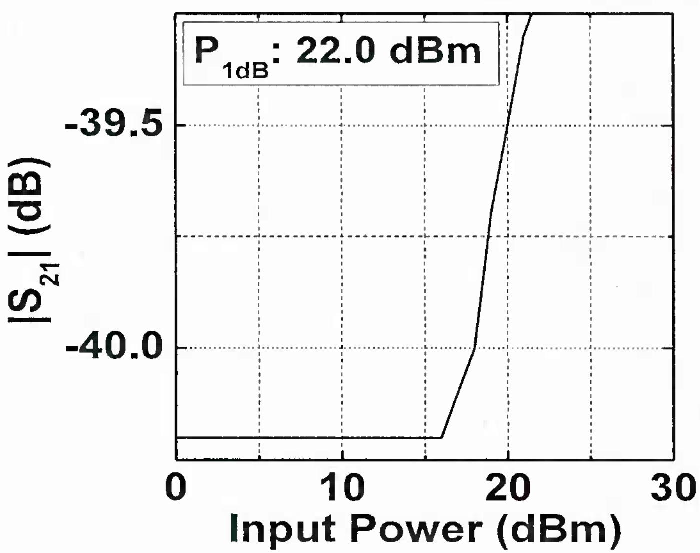
Heat transfer function
Frequency response up to 1 MHz

Y. Shim and M. Rais-Zadeh, IEEE EDL, 2014

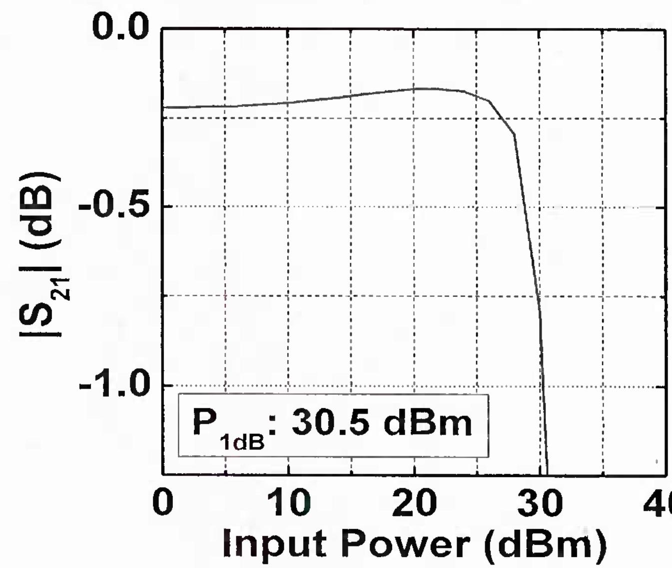
GeTe Switch with Direct Heating - Type A
Simulated P_{1dB} with modeling parameters







@ OFF state, f_c: 1 GHz

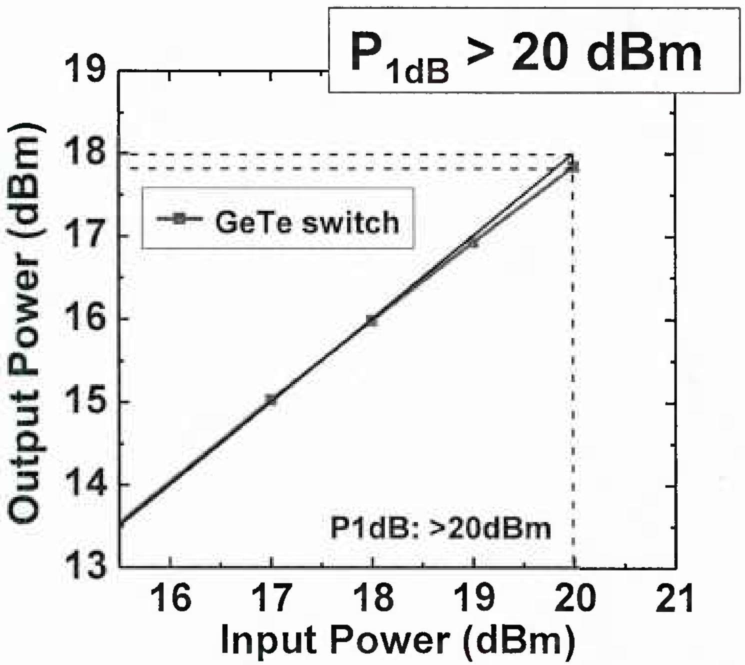


@ ON state, f_c: 1 GHz

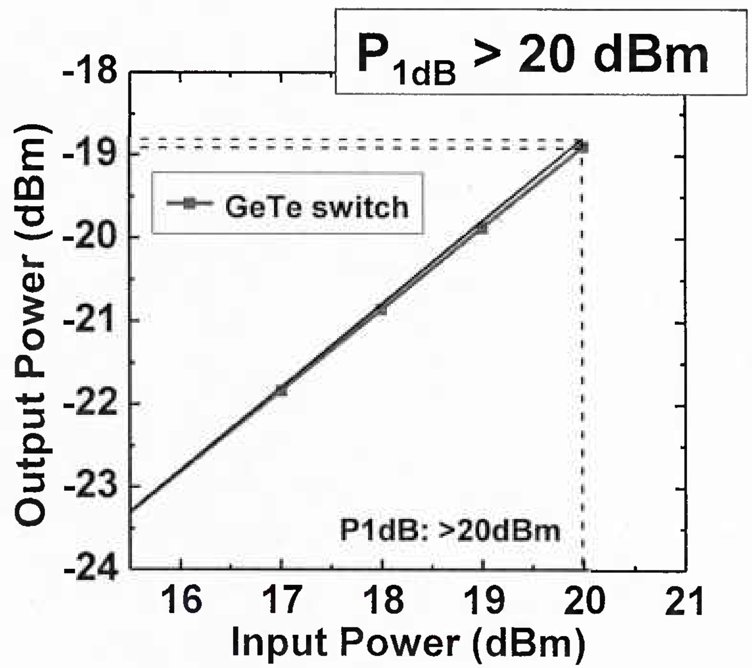
Y. Shim and M. Rais-Zadeh, IEEE EDL, 2014

GeTe Switch with Direct Heating - Type A Measured P_{1dB}

- P_{1dB} is also measured at both crystalline and amorphous states.
- Due to the tool limitation, P_{1dB} is only verified to be better than 20 dBm.



Measured P_{1dB} at 1 GHz
(Crystalline state)



Measured P_{1dB} at 1 GHz
(Amorphous state)

Y. Shim and M. Rais-Zadeh, IEEE EDL, 2014

GeTe Switch with Direct Heating - Type A Simulated IIP_3 with modeling parameters

- IIP_3 is simulated with modeling parameters.
- Smaller offset frequency provides worse IIP_3 due to low-pass filtering effect in the heat transfer function.

#	State	F_C (GHz)	ΔF (KHz)	δ	IIP_3:MODEL (dBm)
1	OFF	0.5	50	1.0	27.1
2	OFF	0.5	1000	1.0	27.2
3	OFF	2.0	50	1.0	33.2
4	OFF	0.5	50	0.2	34.1
5	ON	0.5	**50**	1.0	**36.7**
6	ON	0.5	**1000**	1.0	**39.1**
7	ON	2.0	50	1.0	36.7
8	ON	0.5	50	0.2	50.7

Y. Shim and M. Rais-Zadeh, IEEE EDL, 2014

GeTe Switch with Direct Heating - Type A Simulated IIP_3 with modeling parameters

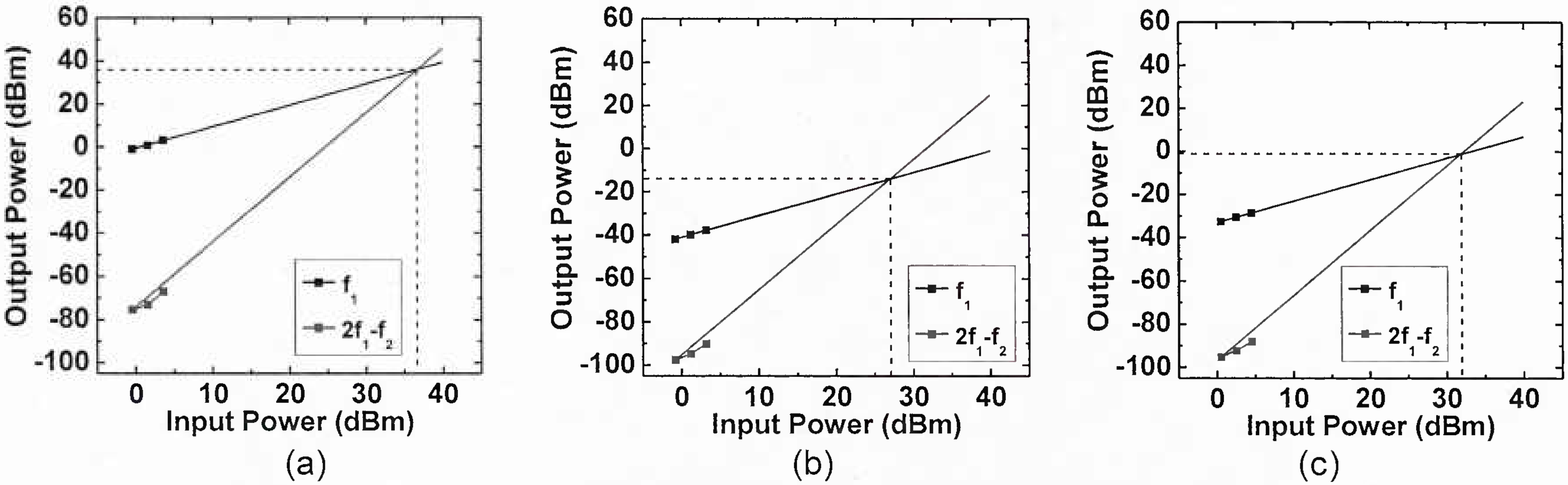
- IIP_3 is simulated with modeling parameters.
- Center frequency does not have any effect on IIP_3 at the ON state.
- Higher center frequency result in better IIP_3 at the OFF state.

#	State	F_C (GHz)	ΔF (κHz)	δ	IIP_3:MODEL (dBm)
1	**OFF**	**0.5**	50	1.0	**27.1**
2	OFF	0.5	1000	1.0	27.2
3	**OFF**	**2.0**	50	1.0	**33.2**
4	OFF	0.5	50	0.2	34.1
5	**ON**	**0.5**	50	1.0	**36.7**
6	ON	0.5	1000	1.0	39.1
7	**ON**	**2.0**	50	1.0	**36.7**
8	ON	0.5	50	0.2	50.7

Y. Shim and M. Rais-Zadeh, IEEE EDL, 2014

GeTe Switch with Direct Heating - Type A Measured IIP_3 with

- IIP_3 of fabricated devices is measured at both states.
- Better IIP_3 is observed at ON state (expected).
- Better IIP_3 in the amorphous state is observed at higher frequencies (feed-through capacitance dominated region).
- IIP_3 does not show much frequency dependency at crystalline state.



Measured IIP_3 at the ON state with f_1: 2 GHz, Δf: 50 kHz (IIP_3: 35.9 dBm). Measured IIP_3 at the OFF state (b) f_1: 500 MHz, Δf: 50 kHz (IIP_3: 27.0 dBm); (c) f_1: 2 GHz, Δf: 50 kHz (IIP_3: 31.9 dBm).

Y. Shim and M. Rais-Zadeh, IEEE EDL, 2014

GeTe Switch with Direct Heating - Type A Simulation / Measurement Result

- IIP_3 of fabricated devices is measured at both states.
- Better IIP_3 is observed at ON state (predicted).
- Measurements and simulations are in very good agreement.

#	State	F_C (GHz)	ΔF (kHz)	δ	IIP_3:MODEL (dBm)	IIP_3:MEASURED (dBm)
1	OFF	0.5	50	1.0	27.1	27.0
2	OFF	0.5	1000	1.0	27.2	-
3	OFF	2.0	50	1.0	33.2	31.9
4	OFF	0.5	50	0.2	34.1	-
5	ON	0.5	50	1.0	36.7	35.9
6	ON	0.5	1000	1.0	39.1	-
7	ON	2.0	50	1.0	36.7	35.9
8	ON	0.5	50	0.2	50.7	-

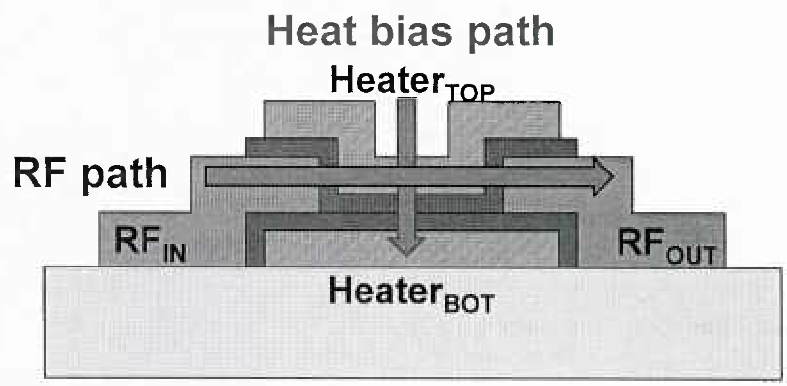
Y. Shim and M. Rais-Zadeh, *IEEE EDL*, 2013, submitted.

Outline

- Motivation & Introduction
- GeTe Vias as RF Ohmic Switches
  - Intrinsic RF Properties
  - Phase-Transition Characteristics
  - Power Handling Capability
- **New GeTe Switch Design**
  - **Design Consideration**
  - **RF & Heat Simulation**
  - **Measurement Results**
- Future Plans

GeTe Switch with Separate Electrodes - Type B
New Design Consideration

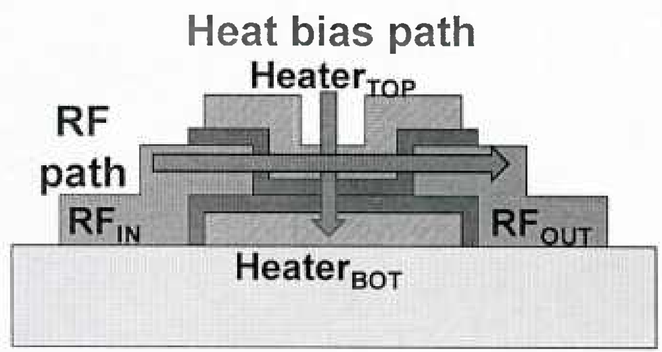
- The previous design is built for basic characterization of GeTe.
- For more reliable phase-transition and better isolation, heater and RF electrodes are separated.

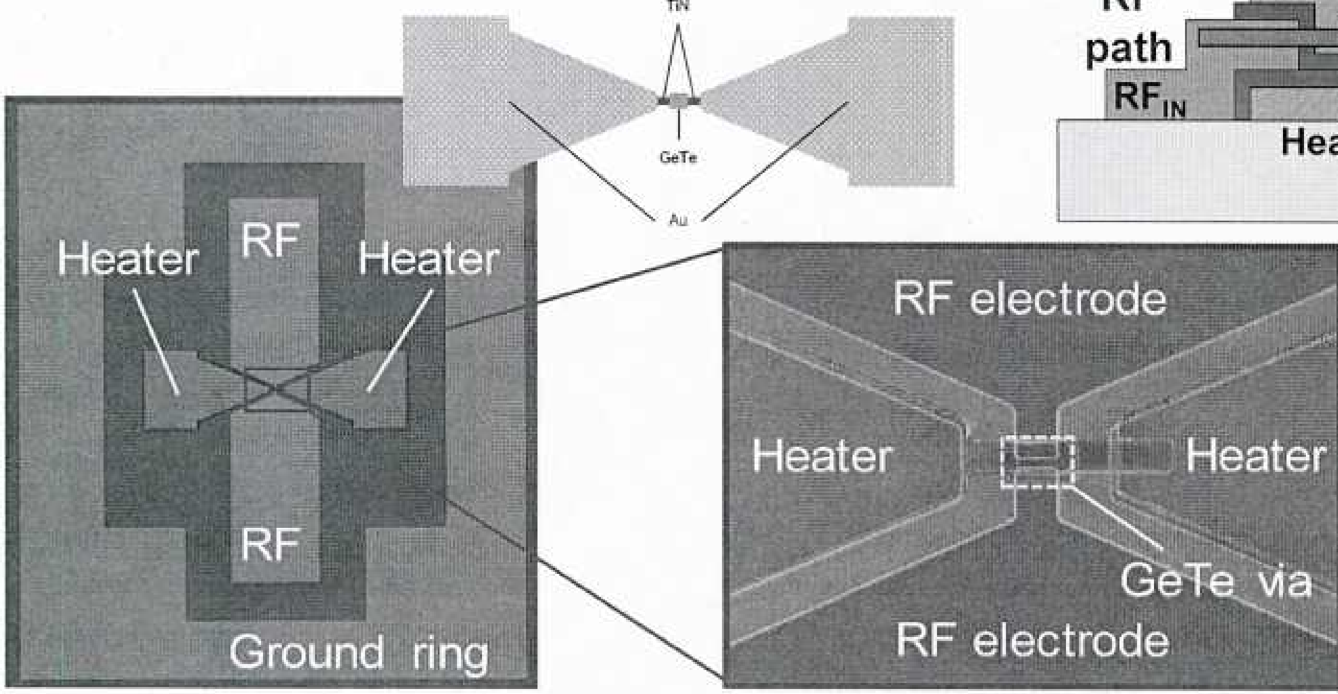


- In this new design, heater bias and RF signal paths are separated while still maintaining a direct heating scheme.
  - More convenient, lower power, and easier transition with direct heating.
  - Heater bias path can be optimized for more reliable transitions.
  - RF path can be optimized for lower loss and better isolation.

GeTe Switch with Separate Electrodes - Type B Device Principle of Operation

- Two GeTe layers are included to provide separation of RF electrodes and heater electrodes.
- Heater electrodes are composed of high-resistivity material for more effective Joule heating.

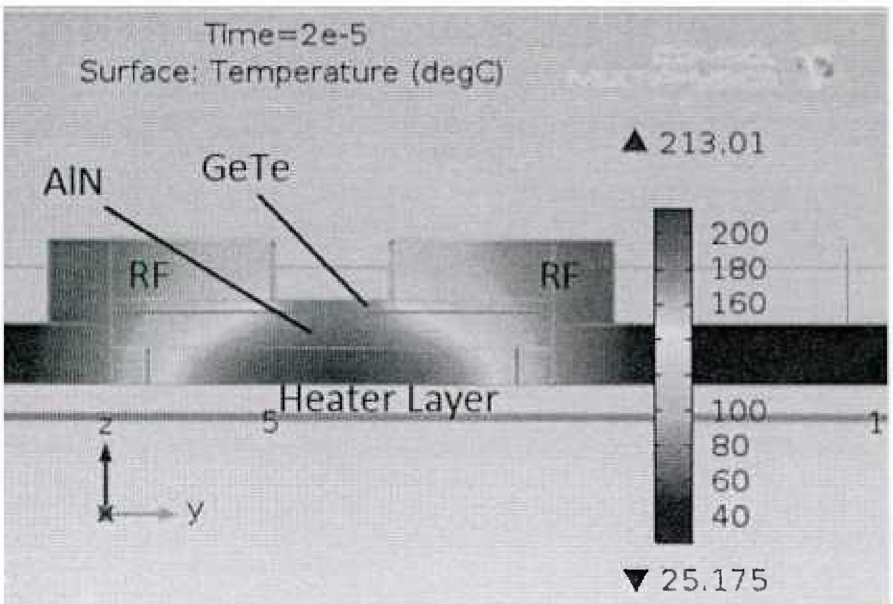


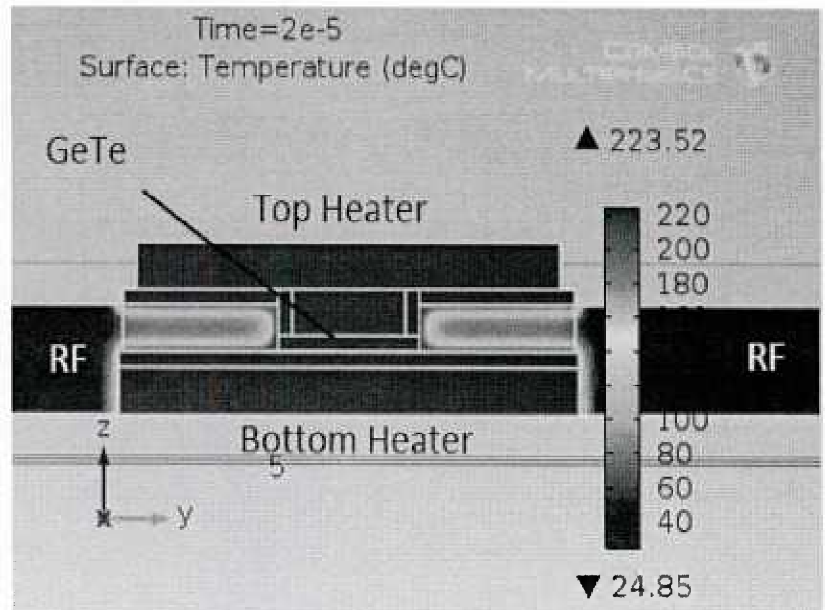


M. Wang and M. Rais-Zadeh, *IEEE IMS*, 2014, submitted.

GeTe Switch with Separate Electrodes - Type B Heat Simulation

- The most important advantage of direct heating scheme is that lower power is required to phase transition the via.
- It also does not have the problem of local cold spot at low power levels.
- Simulations are performed using COMSOL.

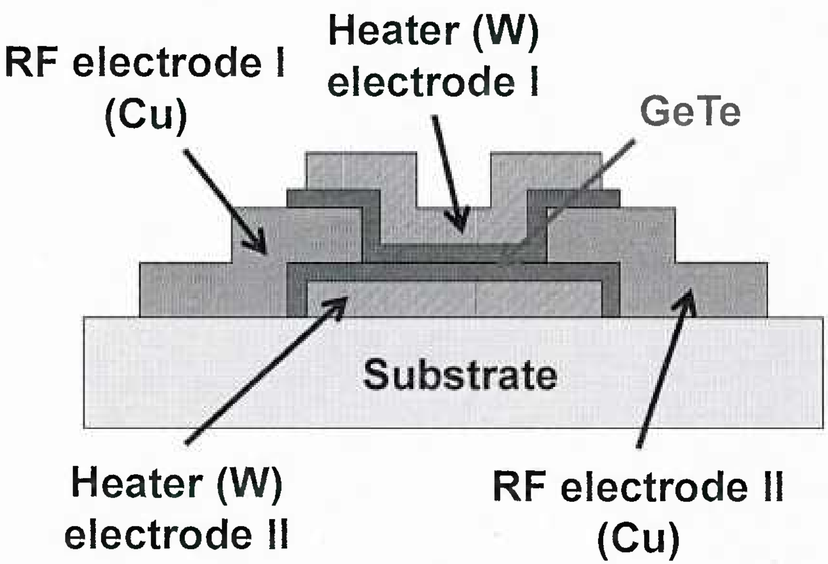




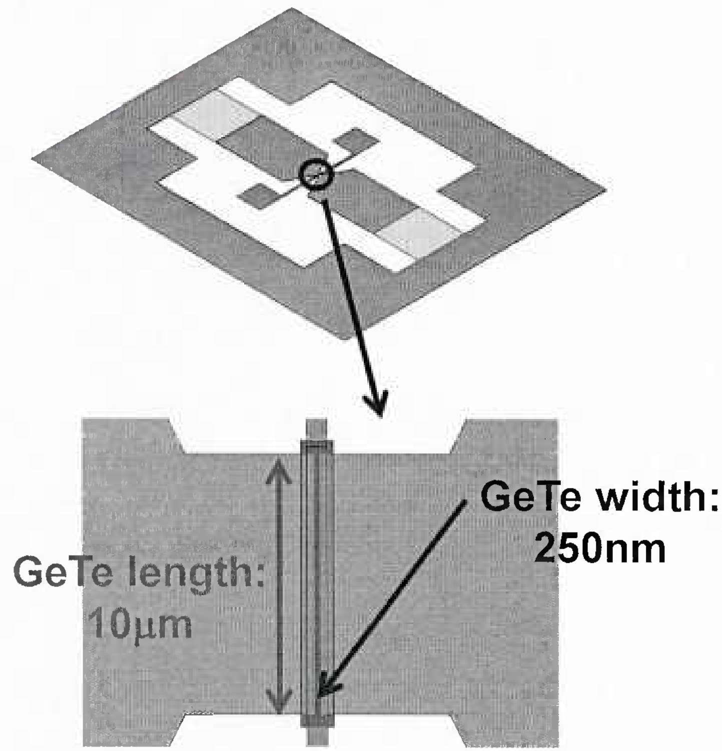
Cross-section view of temperature distribution when a 20 μs current pulse of (left) 50 mA is applied to an indirectly heated via, and (right) 5.5 mA is applied to the presented directly heated via

GeTe Switch with Separate Electrodes - Type B RF Simulation

- For verification of the RF performance, 3D electromagnetic simulation using HFSS is performed.
- Each simulation is performed with different widths and lengths for the switch via.



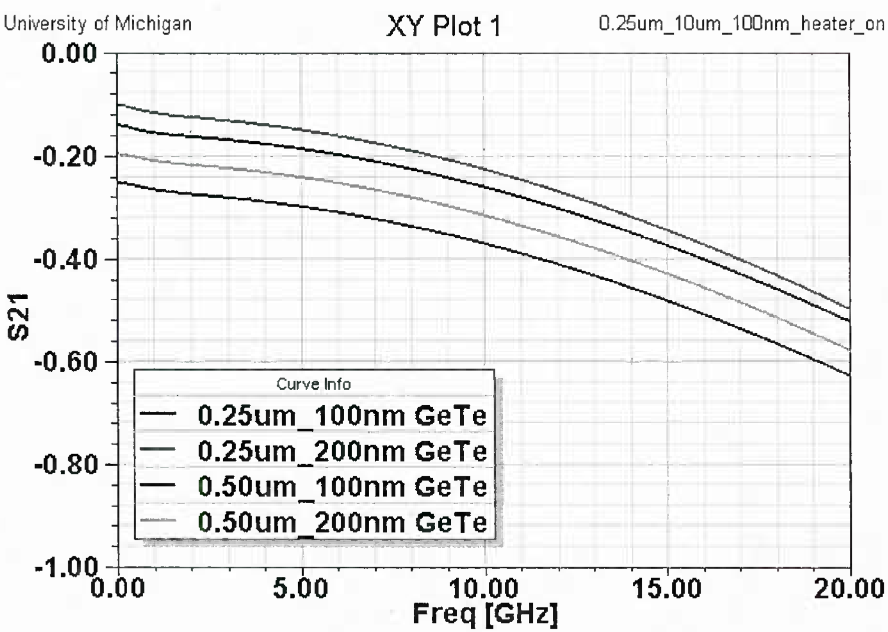
Schematic diagram of GeTe switch with direct heating structure



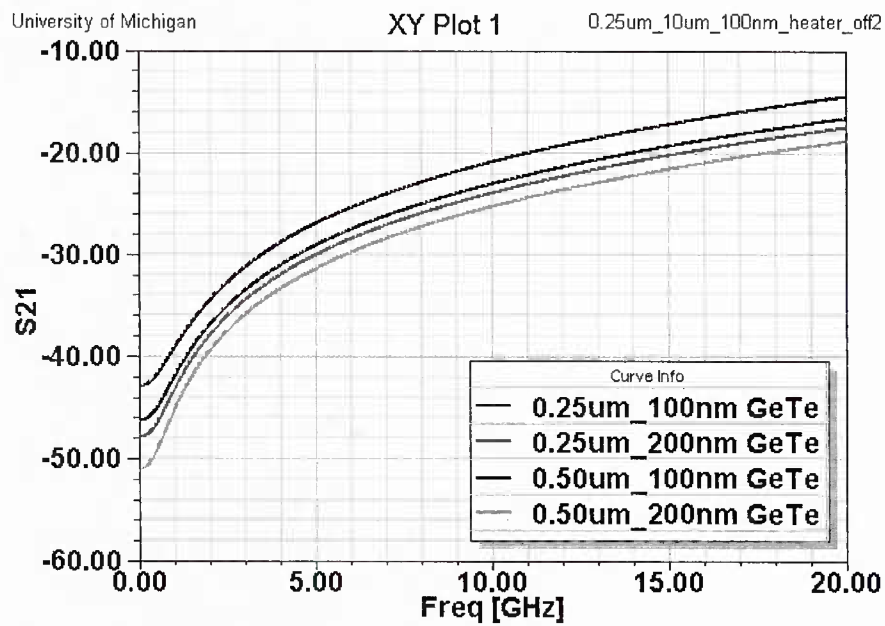
3D model and top-down view of GeTe switch with direct heater for HFSS simulation

GeTe Switch with Separate Electrodes - Type B RF Simulation Results

- As the width of GeTe via increases (0.25 to 0.50 μm), isolation is improved while insertion loss is exacerbated. Thicker GeTe layer can compensate this with reduced resistance; smaller parasitic capacitance between RF electrode and heater layer can further improve the isolation.



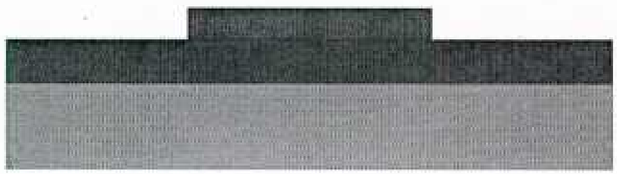
Simulated S_{21} at the crystalline state with different length and thickness of GeTe via.



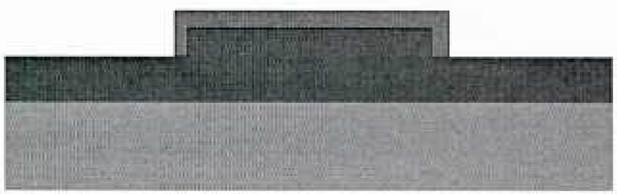
Simulated S_{21} at the amorpheous state with different length and thickness of GeTe via.

GeTe Switch with Separate Electrodes - Type B Fabrication Process

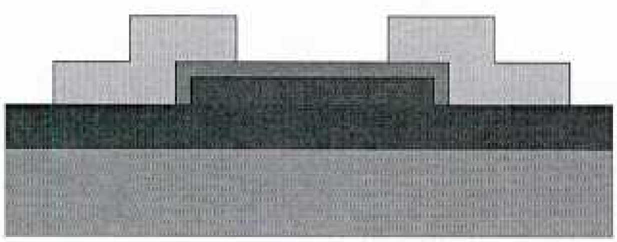
1. Bot. heater layer deposition (TiN or other HR metals) on a Si passivated with AlN



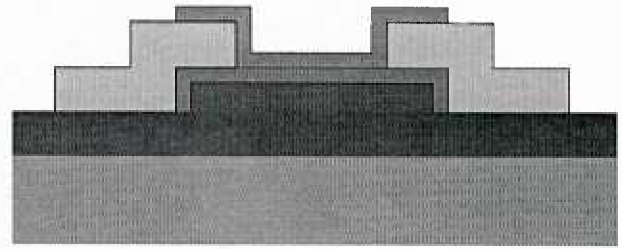
2. 1st GeTe layer deposition



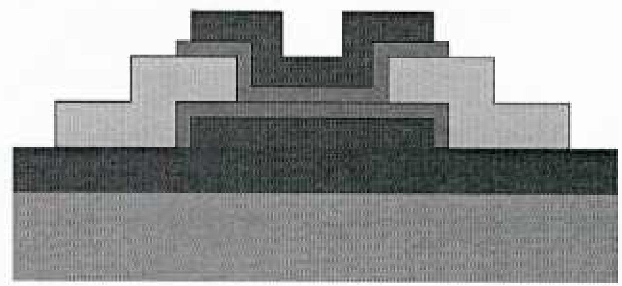
3. RF electrode deposition (Ti/Au/Ti)



4. 2nd GeTe layer deposition



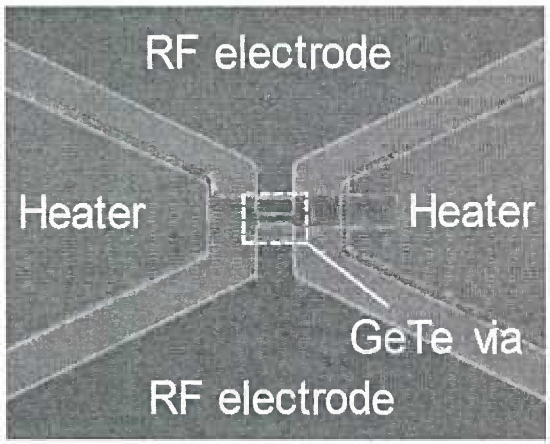
5. Top heater layer deposition (TiN or TaN)



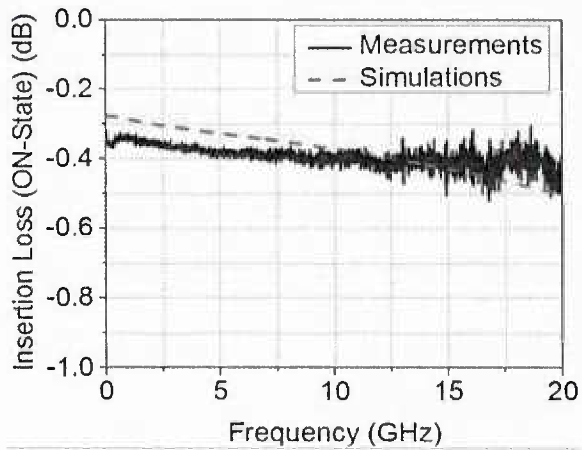
M. Wang and M. Rais-Zadeh, *IEEE IMS*, 2014,
nominated for best student paper award

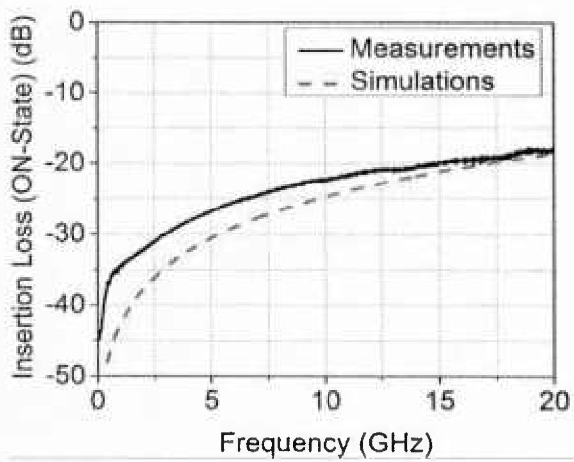
GeTe Switch with Separate Electrodes - Type B Measurement Result: R_{on} & R_{off}

- Preliminary devices are fabricated on a Silicon substrate with AIN Passivation layer.
- Results show promising performance w/ cutoff frequency> 4.1 THz (note that these are measured on Silicon).
- This is the first 4-terminal directly heated phase change switch. IL can be improved by reducing the spacing between RF electrodes.



SEM image of a 4-terminal directly heated GeTe switch



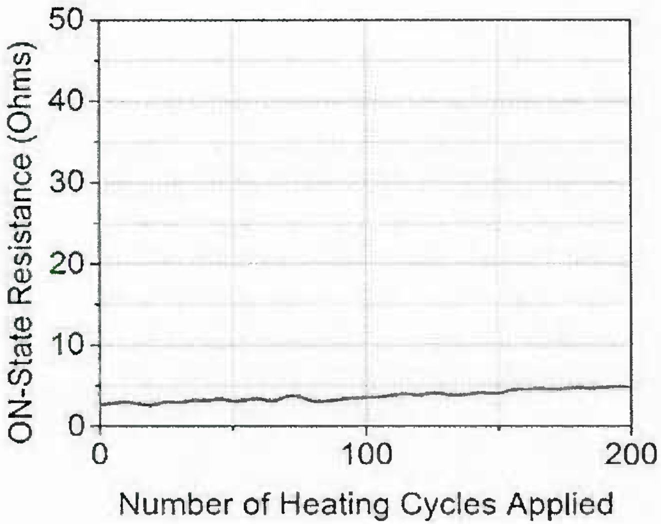


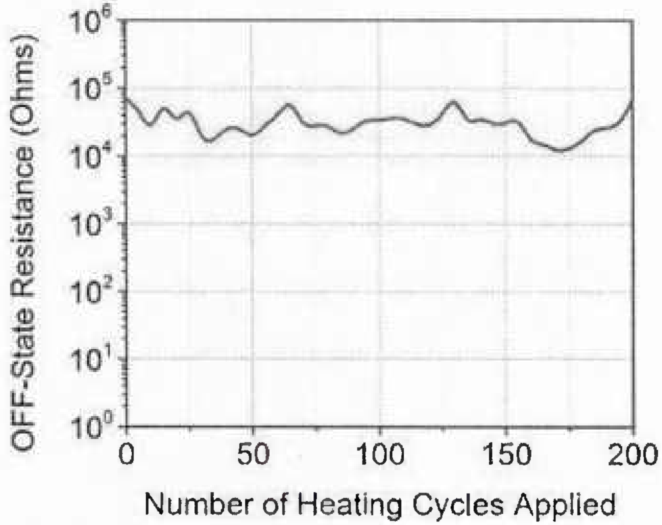
Measured Response of the switch, left: ON state IL; Right: OFF state isolation.

M. Wang and M. Rais-Zadeh, *IEEE IMS*, 2014

GeTe Switch with Separate Electrodes - Type B Life Cycle

- **Switches are manually cycles (need to automate this).**
- **The power consumption of the switch is smaller than indirectly heated switches by more than an order of magnitude[1].**





DC resistance values versus the number of heating cycles applied at (left) the crystalline state and (right) the amorphous state.

[1] N. El-Hinnawy, *et al.*, "A Four-terminal, inline, chalcogenide phase-change RF switch using an independent resistive heater for thermal actuation," *IEEE Electron Device Letters*, vol. 34, no. 10, pp. 1313-1315, Oct. 2013.

M. Wang and M. Rais-Zadeh, *IEEE IMS*, 2014.

GeTe Switch with Separate Electrodes - Type B Simulation Result: IIP_3

- **Higher power RF signal can contribute unintended crystallization or amorphization effect in Type B switch when its effective ON-resistance is the same as Type A switch.**

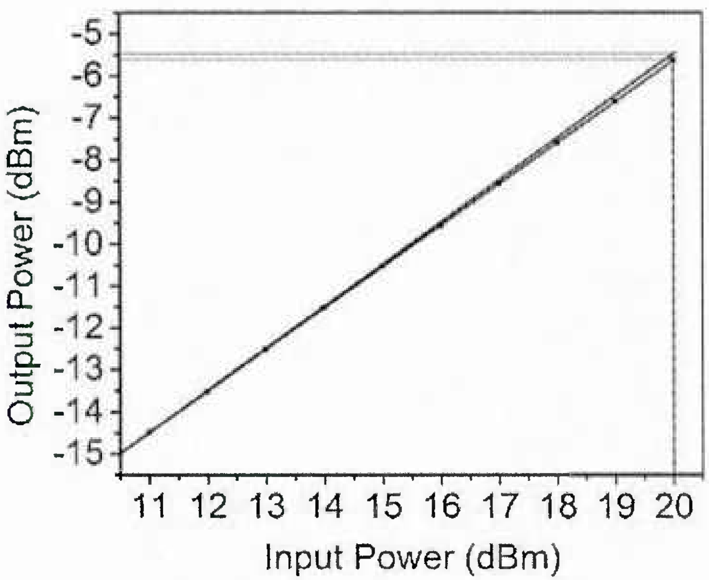
#	State	F_C (GHz)	ΔF (kHz)	IIP_3:MODEL (dBm) Type A	IIP_3:MODEL (dBm) Type B
1	OFF	0.5	50	27.1	32.1
2	OFF	0.5	1000	27.2	32.6
3	OFF	2.0	50	33.2	38.1
5	ON	0.5	50	36.7	40.5
6	ON	0.5	1000	39.1	41.0
7	ON	2.0	50	36.7	40.5

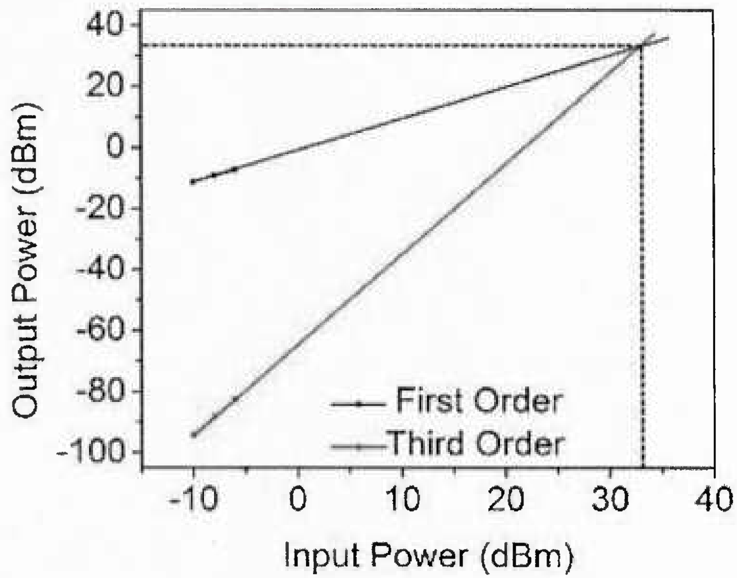
Simulated IIP_3 for different f_c and Δf

M. Wang, Y. Shim, and M. Rais-Zadeh, *IEEE EDL*, 2014

GeTe Switch with Separate Electrodes - Type B Measurement Result: IIP_3

- Measured $IIP_3 > 33$ dBm.
- P_1dB cannot be measured but higher than 20 dBm.
- Results in good agreement with the electro-thermal model.

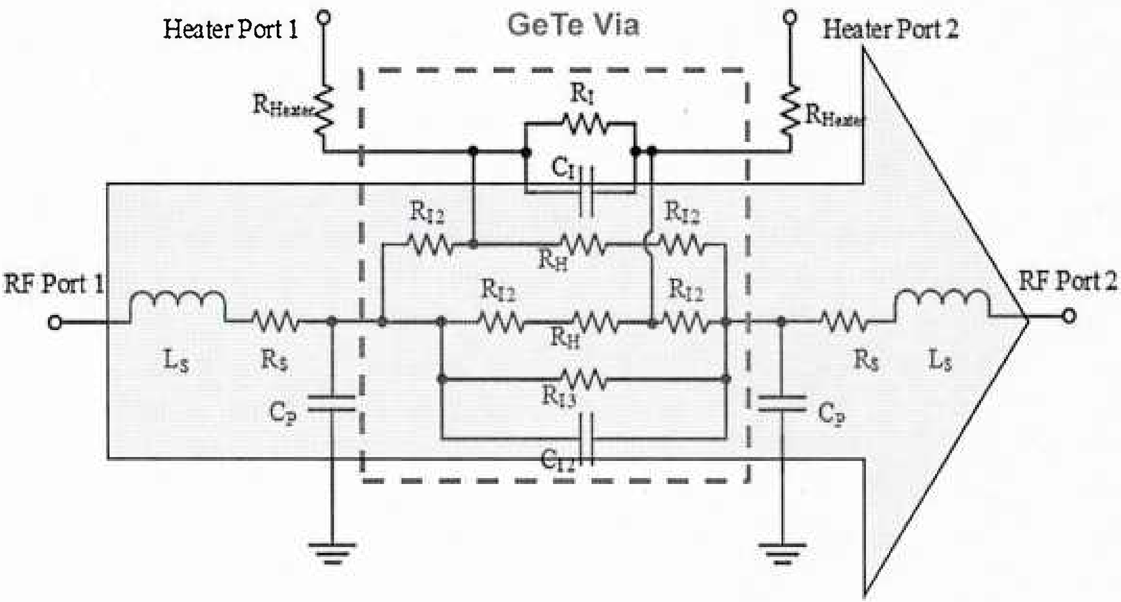


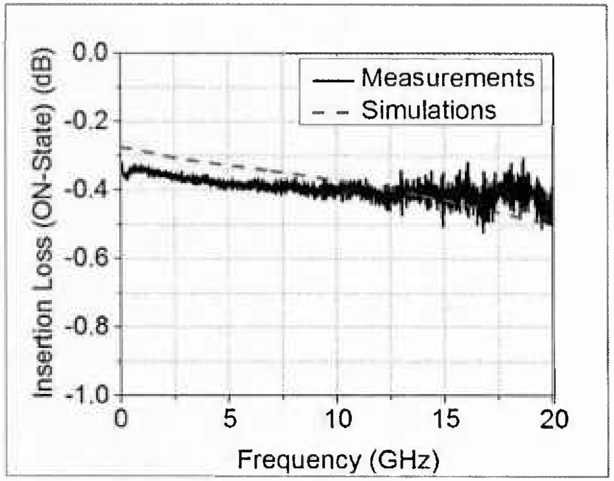


Measured P_1dB (@2GHz, OFF-state) and
IIP_3 (@2GHz, 50 kHz offset, ON state)

M. Wang, Y. Shim, and M. Rais-Zadeh, *IEEE EDL*, 2014

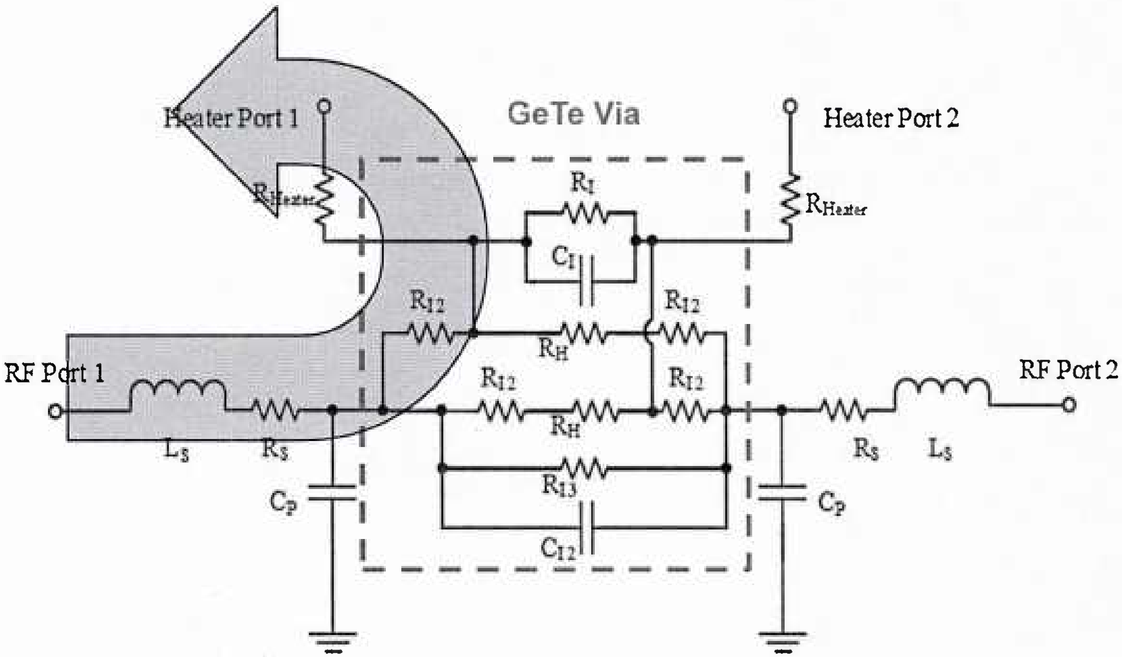
GeTe Switch with Separate Electrodes - Type B Electrical Model

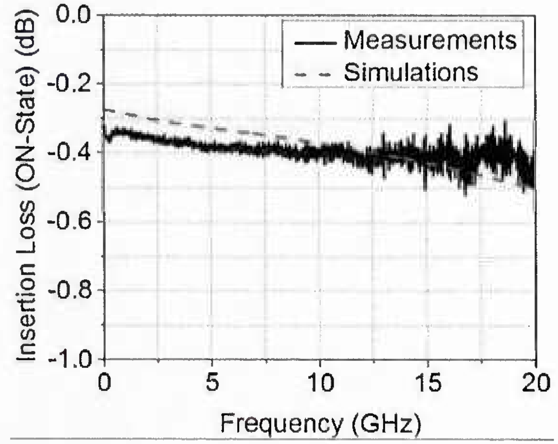


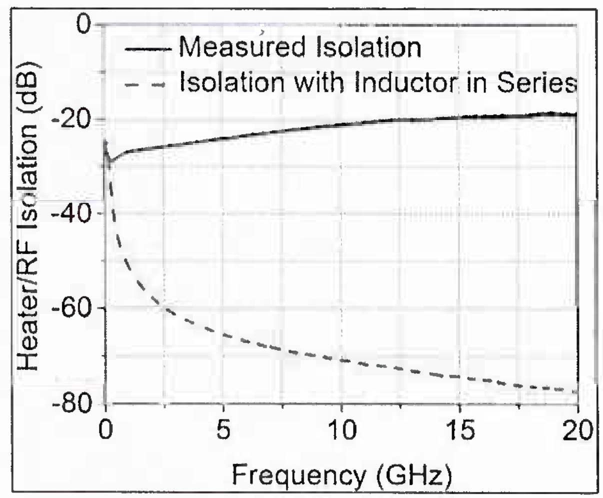


M. Wang, Y. Shim, and M. Rais-Zadeh, *IEEE IMS*, 2014

GeTe Switch with Separate Electrodes - Type B Electrical Model







M. Wang, Y. Shim, and M. Rais-Zadeh, *IEEE IMS*, 2014

GeTe Switch with Separate Electrodes - Type B Summary of Results

	[1]	[2]	[3]
ON-state DC resistance	1.2 Ω	5 Ω	3.9 Ω
OFF/ON resistance ratio	9.2×10^4	0.96×10^4	$\sim0.5\times10^4$
Insertion loss at 20 GHz	< 0.3 dB	< 0.6 dB	< 0.5 dB
Isolation at 20 GHz	12 dB	20 dB	> 18 dB
Via Capacitance (C_{OFF})	18.1 fF	8.5 fF	9.9 fF
Cut-off Frequency	7.3 THz	3.7 THz	> 4.1 THz
Switching time per 1 cycle	–	600.5 μs	404 μs
Power consumption per cycle	4.5 W	92 mW	82 mW
P_{1dB}	> 35 dBm	>20 dBm	> 20 dBm
IIP_3	–	33 dBm	> 30 dBm

[1] N. El-Hinnawy, *et al.*, *IEEE EDL*, vol. 34, no. 10, pp. 1313-1315, Oct. 2013.
[2] M. Wang, Y. Shim, and M. Rais-Zadeh, *IEEE EDL*, 2014
[3] M. Wang and M. Rais-Zadeh, *IEEE IMS*, 2014

GeTe Switch with Separate Electrodes - Type B Summary of Results

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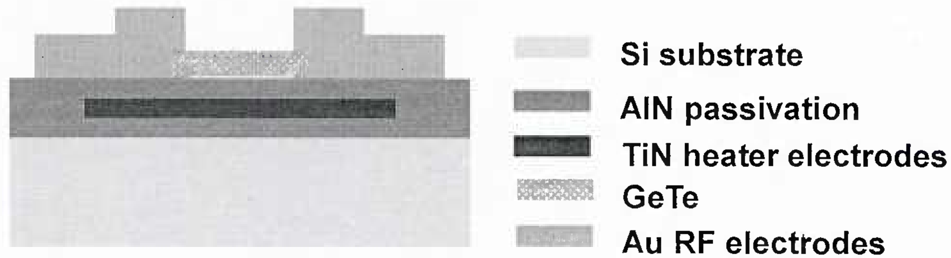
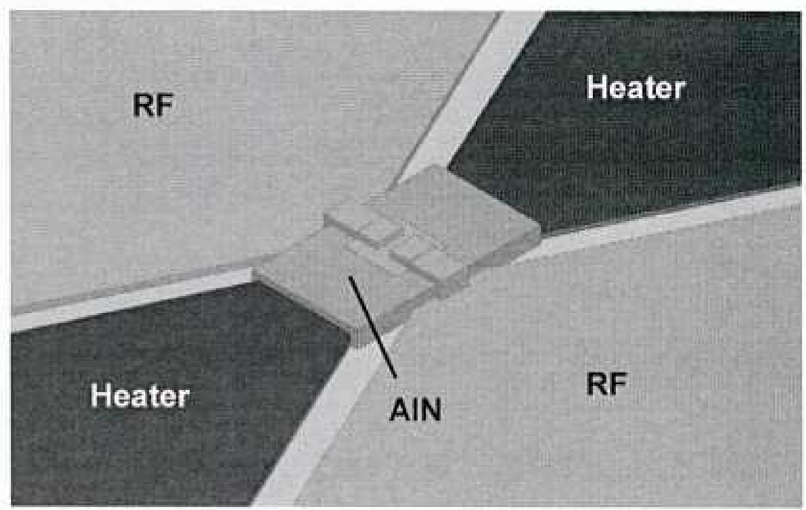
P_{1dB}	> 35 dBm	>20 dBm	> 20 dBm
IIP_3	–	33 dBm	> 30 dBm

[1] N. El-Hinnawy, *et al.*, *IEEE EDL*, vol. 34, no. 10, pp. 1313-1315, Oct. 2013.
[2] M. Wang, Y. Shim, and M. Rais-Zadeh, *IEEE EDL*, 2014
[3] M. Wang and M. Rais-Zadeh, *IEEE IMS*, 2014

GeTe Switch with Separate Electrodes - Type C Indirect Heating Scheme

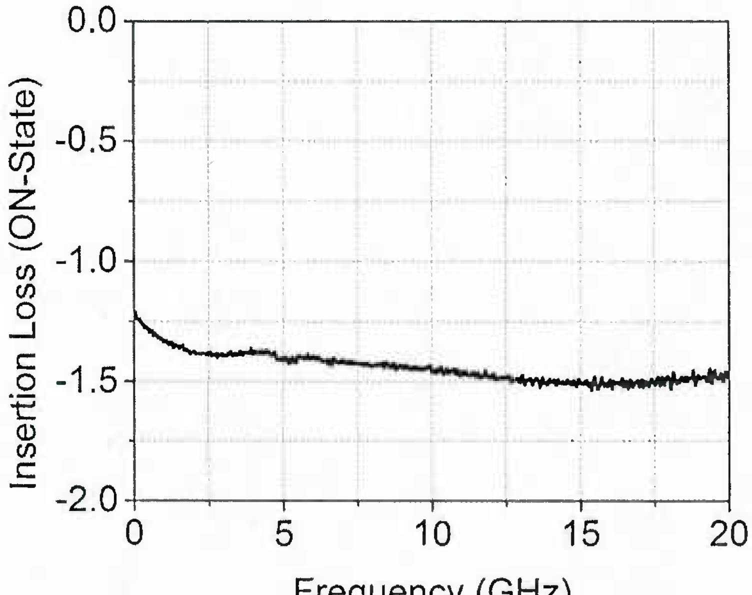
- Electrical isolation between heater and RF path
- Heater layer underneath GeTe with AlN isolation
- RF electrodes laterally connected
- GeTe heated through thermal conduction
- Parasitic elements are significantly reduced
- Promising for high-frequency operation
- Fabrication and measurements ongoing



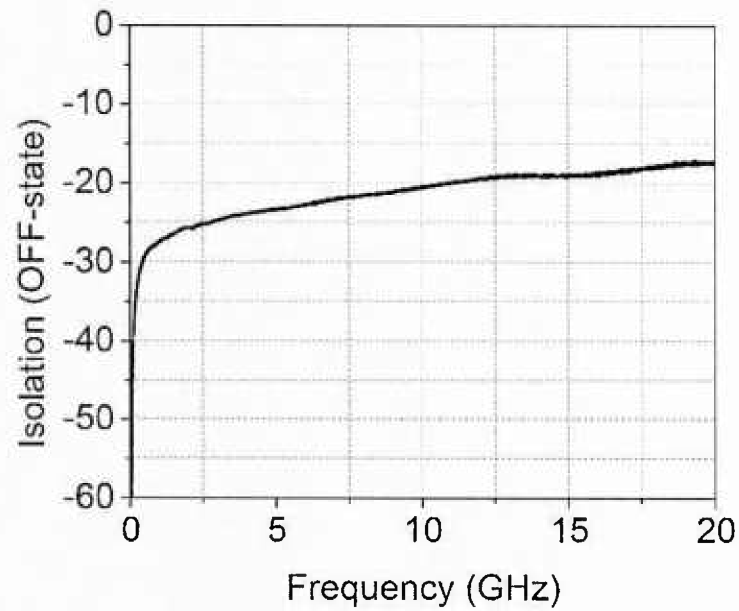


GeTe Switch with Separate Electrodes - Type C Preliminary Results

- **S-parameters Measurements**
  - Initial ON-state insertion loss: 1 to 2 dB
  - Off-state isolation: ~18 dB at 20 GHz
  - Initial DC ON resistance: ~10 Ω
  - Typical initial OFF resistance: ~ 70 kΩ



Initial state

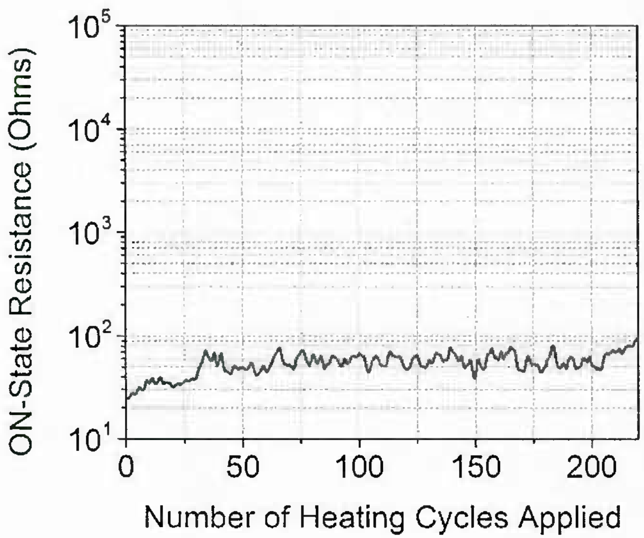


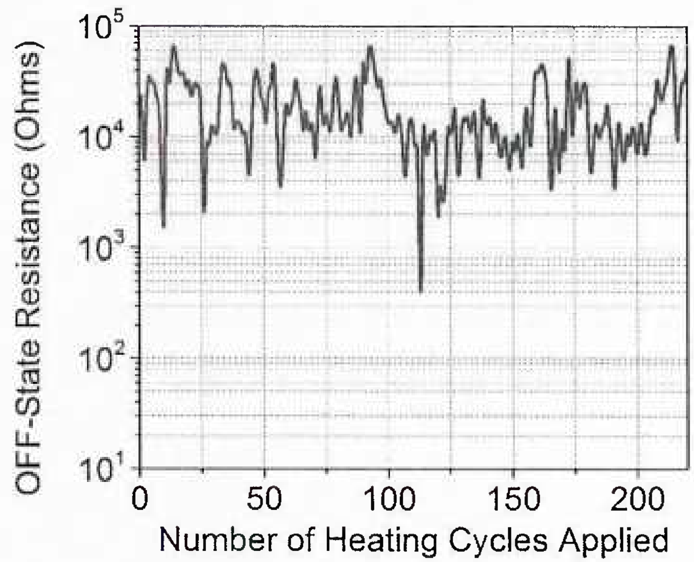
Amorphization (V = 13.9 V)

GeTe Switch with Separate Electrodes - Type C Repeatability

- **Repeated heating pulses applied (220 cycles)**

- **ON-state resistances**
  - **~10 Ω – 50 Ω**
  - **Can be improved by changing size**
- **OFF-state resistances**
  - **Typically 5 kΩ - 70 kΩ**





Outline

- Motivation & Introduction
- GeTe Vias as RF Ohmic Switches
  - Intrinsic RF Properties
  - Phase-Transition Characteristics
  - Power Handling Capability
- New GeTe Switch Design
  - Design Consideration
  - RF & Heat Simulation
  - Initial Measurement Result
- **Future Plans**

Program Schedule

- **Single task; 1 year seedling project.**
- **Proposal: support 1 student.**
- **Project started officially in Jan 2013; received funding in two increments (last one received in Jan. 2014).**

Subtask #	Description of activities	Phase I			
		Q1	Q2	Q3	Q4
ST1	Design and simulation of optimized device architecture to achieve the proposed performance specs and metrics				
ST2	Development and optimization of fabrication process including choice of heater material/contact metal/ and stack thickness				
	Fabrication of micro devices using resistance change materials				
ST3	Test and characterization of DC performance of switches including ON-resistance and ON/OFF resistance Ratio				
	Test and characterization of RF performance of switches including insertion loss, parasitic capacitance, and power handling capability				
Deliver-ables	Submit quarterly report to DARPA				
	Deliver 5 functional samples				

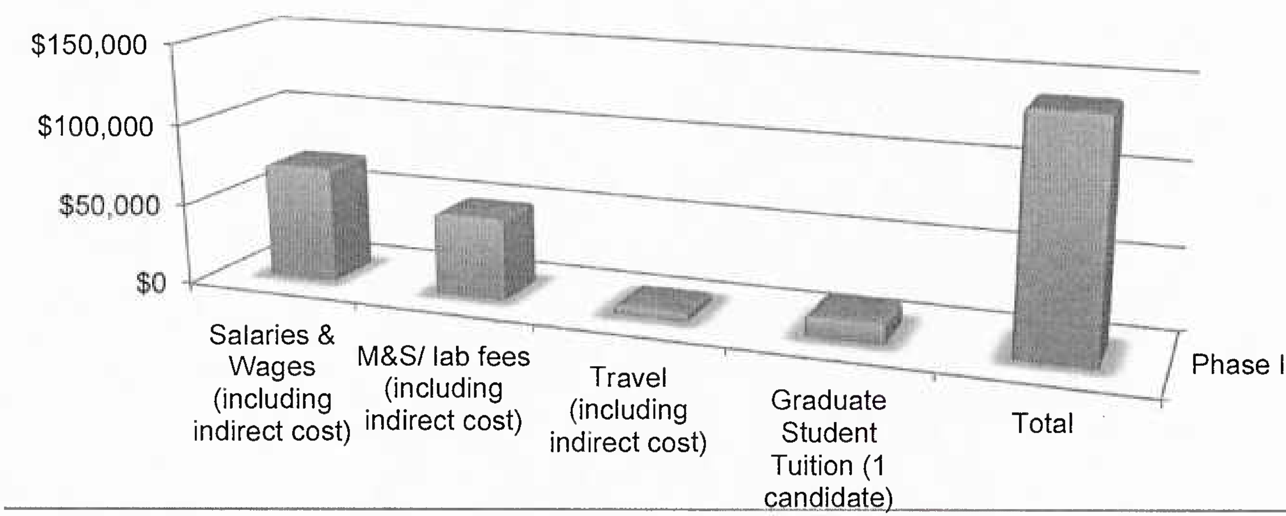
Future Plans

- GeTe switch – directly heated: optimize fabrication process & stack materials/ characterize power handling capability / test repeated cycling (currently manually cycled).
- GeTe switch – indirectly heated: change via size to reduce via resistance; Characterize optimal heating condition to best crystallize GeTe; Use two GeTe layers; Use top passivation to protect GeTe and get better heating conditions; Characterize best RF electrode material to minimize damage to GeTe (e.g., diffusion)
- Preparation of heating current biasing system.
- Preparation of long life cycling test setup.
- Funding: will discuss separately.
  - One student graduated. The undergrad student working on this project continued now as a PhD student. Also a post-doc is recently hired.

Funding Status-Proposed

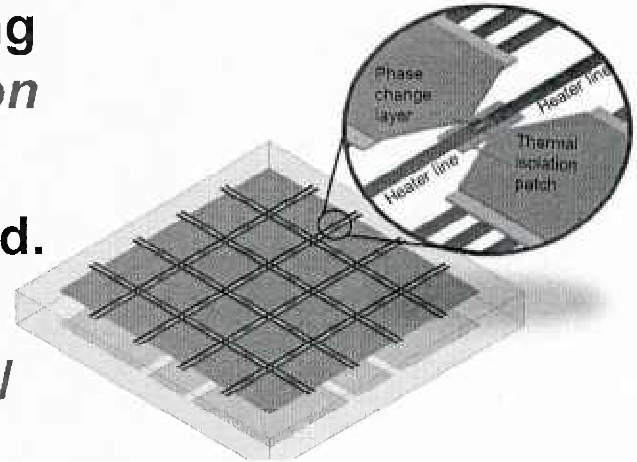
- **Single task; 1 year seedling project.**
- **Proposal: support 1 student.**
- **Project started officially in Jan 2013; received funding in two increments (last one received in Jan. 2014).**

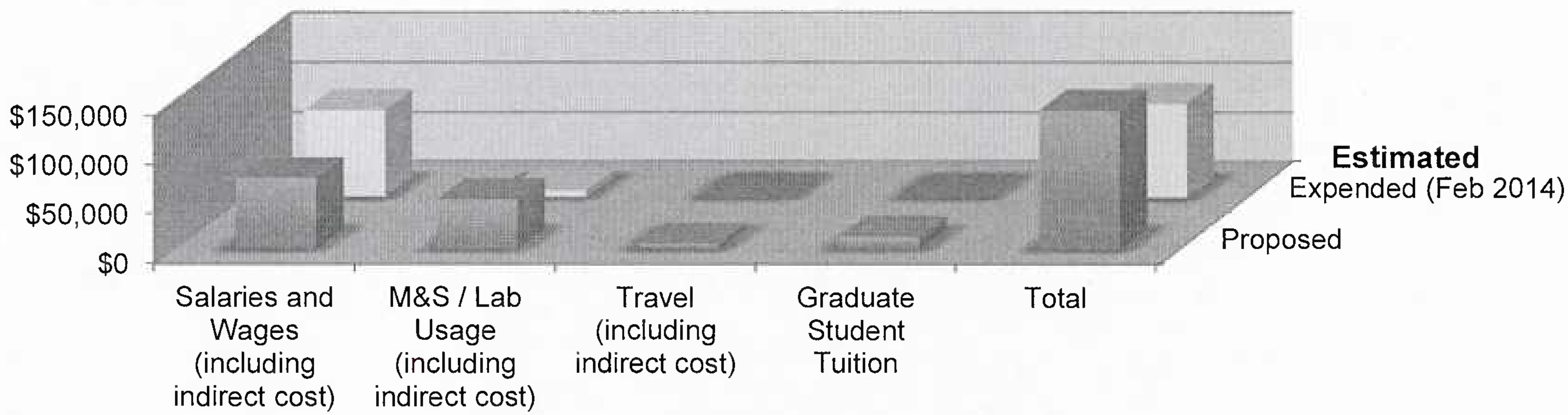
Categories and Timeline	Total (1/10/13-8/31/14)
Salaries & Wages (including indirect cost)	$71,628
M&S/ lab fees (including indirect cost)	$50,664
Travel (including indirect cost)	$5,443
Graduate Student Tuition (1 candidate)	$12,428
Total	$140,163



Funding Status- Update

- One student graduated (joined Broadcom). The undergrad student working on this project continued now as a PhD student. Also a post-doc is recently hired.
- Project started officially in Jan 2013. Funding spent as proposed. Now in *no cost extension* till 5/31/2014.
- Proposal submitted to ACT (w/ SRC) rejected.
- Requesting funding for 2 years to work on various aspects of RF phase change switch/ switch network.





Funding Status- Proposed Budget

Categories and Timeline	Year 2 6/1/14 - 5/31/15	Year 3 6/1/15 - 5/31/16	Total 6/1/14 - 5/31/16
Direct Salaries and Wages			
Prof. M. Rais-Zadeh, Project Director			
5% Academic Year	$5,202	$5,358	$10,559
25% 2 Summer Months	$5,611	$5,779	$11,391
Post-Doctoral Research Fellow			
50%, Full Year	$25,563	$26,329	$51,892
Graduate Student Research Assistants			
1 @ 50% Full Year	$28,528	$29,384	$57,911
Subtotal Salaries and Wages	$64,903	$66,850	$131,753
Staff Benefits @ 20% GSRA, 30% others	$16,618	$17,117	$33,735
SUBTOTAL SALARIES AND BENEFITS	**$81,521**	**$83,967**	**$165,488**
Materials and Supplies			
LNF User Fees, 1 user	$20,000	$20,000	$40,000
Masks (10 Plates)	$3,800	$3,800	$7,600
Glass wafers, Si Wafers, Sapphire wafers	$3,031	$3,031	$6,063
Various Processing Supplies, Chemicals, etc.	$5,000	$5,000	$10,000
Misc. Supplies, telephone charges, mailing, etc.	$2,000	$2,000	$4,000
SUBTOTAL MATERIALS/SUPPLIES	**$33,831**	**$33,831**	**$67,663**
Travel	**$3,500**	**$3,500**	**$7,000**
Graduate Student Tuition (1 non-candidate)	**$21,853**	**$22,945**	**$44,798**
SUBTOTAL EQUIPMENT	$0	$0	$0
Subtotal Direct Costs	$140,705	$144,243	$284,948
Subtotal Indirect Costs (55.5%)	$65,963	$67,320	$133,283
Total	**$206,668**	**$211,563**	**$418,231**